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# Measurement of the $t$ -channel single top-quark production cross section in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector <sup>☆</sup>

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## ABSTRACT

We report a measurement of the cross section of single top-quark production in the  $t$ -channel using  $1.04 \text{ fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 7$  TeV recorded with the ATLAS detector at the LHC. Selected events feature one electron or muon, missing transverse momentum, and two or three jets, exactly one of them identified as originating from a  $b$  quark. The cross section is measured by fitting the distribution of a multivariate discriminant constructed with a neural network, yielding  $\sigma_t = 83 \pm 4$  (stat.)  $^{+20}_{-19}$  (syst.) pb, which is in good agreement with the prediction of the Standard Model. Using the ratio of the measured to the theoretically predicted cross section and assuming that the top-quark-related CKM matrix elements obey the relation  $|V_{tb}| \gg |V_{ts}|, |V_{td}|$ , the coupling strength at the  $W$ - $t$ - $b$  vertex is determined to be  $|V_{tb}| = 1.13^{+0.14}_{-0.13}$ . If it is assumed that  $|V_{tb}| \leq 1$  a lower limit of  $|V_{tb}| > 0.75$  is obtained at the 95% confidence level.

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## 1. Introduction

At hadron colliders top quarks are predominantly produced in pairs (top–antitop) via the flavour-conserving strong interaction. Alternative production modes proceed via the weak interaction involving a  $W$ - $t$ - $b$  vertex, leading to a single top-quark intermediate state. Three subprocesses contribute to single top-quark production: the exchange of a virtual  $W$  boson in the  $t$ -channel, or in the  $s$ -channel, and the associated production of a top quark and an on-shell  $W$  boson. The process with the highest cross section at the Tevatron and at the LHC is the  $t$ -channel mode  $q + b \rightarrow q' + t$ .

In 2009, single top-quark production was observed by the CDF [1] and DØ [2] Collaborations based on analyses counting the  $t$ -channel and  $s$ -channel processes as signal. The observation of the  $t$ -channel production mode has also been recently reported by DØ [3], while the CMS Collaboration has published evidence of this process at the LHC [4].

The single top-quark final state provides a direct probe of the  $W$ - $t$ - $b$  coupling and is sensitive to many models of new physics [5]. The measurement of the production cross section constrains the absolute value of the quark-mixing matrix element  $V_{tb}$  [6,7] without assumptions about the number of quark generations (see Ref. [8] for a recent measurement from the DØ Collaboration). Alternatively, it allows the  $b$ -quark parton distribution function (PDF) to be measured.

At the LHC, colliding protons at  $\sqrt{s} = 7$  TeV, the sum of  $t$  and  $\bar{t}$  cross sections is predicted to be:  $\sigma_t = 64.6^{+2.7}_{-2.0}$  pb [9] for the

leading  $t$ -channel process,  $\sigma_{Wt} = 15.7 \pm 1.1$  pb [10] for  $Wt$  associated production, and  $\sigma_s = 4.6 \pm 0.2$  pb [11] for the  $s$ -channel. The analyses presented in this Letter consider only the  $t$ -channel process as signal, while the other two single top-quark processes are treated as backgrounds, assuming the Standard Model (SM) theoretical cross sections for these processes.

The  $W$  boson from the top-quark decay is reconstructed in its leptonic decay modes  $e\nu$ ,  $\mu\nu$  or  $\tau\nu$ , where the  $\tau$  decays leptonically. Thus, selected events contain one charged lepton candidate,  $e$  or  $\mu$ ; two or three hadronic high- $p_T$  jets; and missing transverse momentum  $E_T^{\text{miss}}$ . Two jets are expected from the leading-order (LO) process, while a third jet may arise from higher-order processes. Exactly one of the jets is required to be identified as originating from a  $b$ -quark.

The measurement of  $\sigma_t$  is based on a fit to a multivariate discriminant constructed with a neural network (NN) to separate signal from background and the result is cross-checked using a cut-based method, which additionally provides a breakdown for the  $t$  and  $\bar{t}$  cross sections.

## 2. Data and simulated event samples

The analyses described in this Letter use proton–proton LHC collision data at a centre-of-mass energy of 7 TeV collected with the ATLAS detector [12] between March and June 2011. The selected events were recorded based on single electron and muon triggers. Stringent detector and data quality requirements are applied, resulting in a data set corresponding to an integrated luminosity of  $1.04 \pm 0.04 \text{ fb}^{-1}$  [13,14].

Samples of simulated events for all three single top-quark processes are produced with the ACERMC program (version 3.7) [15]

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using MRST 2007LO\* parton distribution functions (PDFs) [16]. The computation of the  $t$ -channel single top-quark process in ACERMC incorporates the  $q + b \rightarrow q' + t$  and  $q + g \rightarrow q' + t + \bar{b}$  subprocesses and features an automated procedure to remove the overlap in phase space between them [17]. Samples of the top-quark pair ( $t\bar{t}$ ) process are generated using MC@NLO (version 3.41) [18], with the CTEQ6.6 set of PDFs [19]. The top-quark mass is assumed to be 172.5 GeV. Generator default values of 0.999105 and 0.999152 are used for  $|V_{tb}|$  to produce the ACERMC and MC@NLO samples, respectively. At higher orders in perturbation theory, interference effects between the single-top  $Wt$  channel and  $t\bar{t}$  processes occur, but are found to be small [20] and can therefore be safely neglected. The ALPGEN leading-order generator (version 2.13) [21] and the CTEQ6L1 set of PDFs [19] are used to generate  $W + \text{jets}$ ,  $Wb\bar{b}$ ,  $Wc\bar{c}$ ,  $Wc$  and  $Z + \text{jets}$  events with up to five additional partons. To remove overlaps between the  $n$  and  $n + 1$  parton samples the “MLM” matching scheme [21] is used. The double counting between the inclusive  $W + n$  parton samples and samples with associated heavy-quark pair-production is removed utilising an overlap removal based on a  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  matching.<sup>1</sup> The diboson processes  $WW$ ,  $WZ$  and  $ZZ$  are generated using HERWIG (version 6.5.20) [22]. For all single top-quark samples the hadronisation is performed by PYTHIA (version 6.4.25) [23]; in all other cases HERWIG in connection with the JIMMY [24] underlying event model (version 4.31) is used. After the event generation, all samples are passed through the full simulation of the ATLAS detector [25] based on GEANT4 [26] and are then reconstructed using the same procedure as for collision data. The simulation includes the effect of multiple  $pp$  collisions per bunch crossing and is weighted to the same distribution as observed in the data with 5.6 interactions per bunch crossing on average.

### 3. Object definition and event selection

Electron candidates are reconstructed offline using a cluster-based algorithm and are required to have  $E_T > 25$  GeV and  $|\eta_{cl}| < 2.47$ , where  $\eta_{cl}$  denotes the pseudorapidity of the calorimeter cluster. Clusters in the transition regions between the calorimeter barrel and endcaps, corresponding to  $1.37 < |\eta_{cl}| < 1.52$ , are ignored. High-quality electron candidates are selected using a set of cuts [27] which include stringent requirements on the matching between the track and the calorimeter cluster. Electrons must also be isolated: the sum of the calorimeter transverse energy within a cone of radius  $\Delta R = 0.3$  (excluding the cells associated with the electron) must be less than 15% of the electron  $E_T$ , and the  $p_T$  of all tracks within the same cone radius around the electron direction, again excluding the track associated to the electron, must be less than 10% of the electron  $E_T$ .

Muon candidates are reconstructed by combining track segments found in the inner detector and in the muon spectrometer. We only consider muon candidates that have  $p_T > 25$  GeV and  $|\eta| < 2.5$ . Selected muons must additionally satisfy a series of cuts on the number of track hits present in the various tracking sub-detectors [28]. Muon candidates are required to be isolated using the equivalent criteria as applied to electron candidates.

Jets are reconstructed using the anti- $k_t$  algorithm [29] with a radius parameter of 0.4, using clusters of adjacent calorimeter cells [30] as inputs to the jet clustering. The response of the calorimeter is corrected by  $p_T$ - and  $\eta$ -dependent factors [31], which are

applied to each jet to provide an average energy scale correction. Jets overlapping with selected electron candidates within  $\Delta R < 0.2$  are removed, as in these cases the jet and the electron are very likely to correspond to the same physics object. Only jets having  $p_T > 25$  GeV and  $|\eta| < 4.5$  are considered. Jets originating from bottom quarks are tagged in the region  $|\eta| < 2.5$  by reconstructing secondary and tertiary vertices from the tracks associated with each jet and combining lifetime-related information with an NN [32]. A threshold is applied to the  $b$ -tagging algorithm output corresponding to a  $b$ -tagging efficiency of about 57% and a light-quark jet rejection factor (the reciprocal of the efficiency to  $b$ -tag light quarks) of about 520 for jets in  $t\bar{t}$  events. The  $E_T^{\text{miss}}$  is calculated using clusters of adjacent calorimeter cells and corrected for the presence of electrons, muons, and jets [33].

Events are selected if they contain at least one good primary vertex candidate [34] with a minimum of five associated tracks each with  $p_T > 400$  MeV. Events containing jets failing quality criteria [35] are rejected.

The event selection requires exactly one charged lepton,  $e$  or  $\mu$ , exactly two or three jets, and  $E_T^{\text{miss}} > 25$  GeV. A trigger matching requirement is applied where the lepton must lie within  $\Delta R < 0.15$  of its trigger-level object. Since the multijet background is difficult to model precisely, its contribution is additionally reduced through a requirement on the transverse mass of the lepton- $E_T^{\text{miss}}$  system<sup>2</sup>:  $m_T(W) > (60 \text{ GeV} - E_T^{\text{miss}})$  [36].

The following samples are defined for this analysis: a “ $b$ -tagged sample” with two jets or three jets, exactly one of which is  $b$ -tagged, and a “pretag sample” with two or three jets, without making any  $b$ -tagging requirement. We also use a sample containing exactly one  $b$ -tagged jet to estimate the  $W + \text{jets}$  flavour composition.

### 4. Background estimation

A large background to the single top-quark final state comes from QCD-produced multijet events in which either one of the jets is misidentified as an isolated lepton or a non-prompt lepton (for example from a  $b$ -quark semileptonic decay) appears isolated. Other significant backgrounds originate from  $W$ -boson production in association with jets and  $t\bar{t}$  production. Smaller backgrounds come from  $Z + \text{jets}$ ,  $Wt$ -channel and  $s$ -channel single top-quark production, and diboson production. These smaller backgrounds and the  $t\bar{t}$  background are normalised to their theoretical predictions. For the  $Z + \text{jets}$  background the inclusive cross section is calculated to next-to-next-to-leading order (NNLO) with FEWZ (version from March 15, 2009) [37]. The diboson cross sections are normalised to next-to-leading order theoretical calculations [38]. The  $t\bar{t}$  cross section is normalised to the approximate NNLO-predicted value obtained using HATHOR (version 1.2) [39].

The multijet background normalisation is obtained using a binned maximum-likelihood fit to the  $E_T^{\text{miss}}$  distribution in the data, before the application of the  $E_T^{\text{miss}}$  cut, using a data-derived template for the multijet background and templates from Monte Carlo simulation for all other processes (top quark,  $W/Z + \text{jets}$ , dibosons). The multijet template is created using collision events that are triggered by a single low- $p_T$  jet. Several prescaled trigger streams with different  $p_T$  thresholds are used for that purpose. In the offline selection of these events the electron requirement is replaced by a jet requirement (jet-electron model). This jet must have  $p_T > 25$  GeV, the same acceptance in  $|\eta|$  as the signal elec-

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the  $z$ -axis along the beam direction. The  $x$ -axis points towards the centre of the LHC ring, the  $y$ -axis points upwards. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

<sup>2</sup> Defined as  $m_T(W) = \sqrt{(p_T(\ell) + E_T^{\text{miss}})^2 - (p_x(\ell) + E_x^{\text{miss}})^2 - (p_y(\ell) + E_y^{\text{miss}})^2}$ , where  $\ell$  denotes the lepton.

**Table 1**

Predicted and observed event yields, after selection, in the electron and muon 2-jet and 3-jet  $b$ -tagged samples. The multijet event yields are determined with a data-driven technique. Contributions from  $W$  + jets events are normalised to observed data in control regions as used in the cut-based analysis. The uncertainties on the multijet and the  $W$  + jets yields are also estimated from data (see Section 6). All other backgrounds and the  $t$ -channel signal expectation are normalised to theoretical cross sections. Uncertainties on these predictions are only reflecting the uncertainties on the theoretical cross section prediction and do not include experimental uncertainties (such as the jet energy scale uncertainty, etc.).

	Electron		Muon	
	2-jet	3-jet	2-jet	3-jet
Single-top $t$ -channel	447 $\pm$ 11	297 $\pm$ 7	492 $\pm$ 12	323 $\pm$ 8
$t\bar{t}$ , other top	785 $\pm$ 52	1700 $\pm$ 120	801 $\pm$ 53	1740 $\pm$ 130
$W$ + light jets	350 $\pm$ 100	128 $\pm$ 56	510 $\pm$ 150	209 $\pm$ 91
$W$ + heavy flavour jets	2600 $\pm$ 740	1100 $\pm$ 400	3130 $\pm$ 880	1270 $\pm$ 480
$Z$ + jets, diboson	158 $\pm$ 63	96 $\pm$ 44	166 $\pm$ 61	80 $\pm$ 31
Multijet	710 $\pm$ 350	580 $\pm$ 290	440 $\pm$ 220	270 $\pm$ 140
Total expected	5050 $\pm$ 830	3900 $\pm$ 520	5530 $\pm$ 930	3900 $\pm$ 520
Data	5021	3592	5592	3915

tron, and (80–95)% of the jet energy deposited in the electromagnetic section of the calorimeter. The last requirement ensures the orthogonality of the jet-electron data set to the sample of events with electron candidates which feature an electromagnetic energy fraction larger than 95%. The jet must also contain at least four tracks, thus reducing the contribution from converted photons. When selecting the jet-electron sample, events containing electron or muon candidates in addition to the jet-electron are vetoed. The same model is also used in the muon channel. A systematic uncertainty of 50% on the multijet background rates was estimated by studying the impact of pile-up events on the fit results and by performing likelihood fits on the  $m_T(W)$  distribution. The jet-electron model is also used to model the shape of kinematic distributions of the multijet background.

The kinematic distributions of the  $W$  + jets background, which comprises contributions from  $W$  + heavy flavour jets ( $Wb\bar{b}$  + jets,  $Wc\bar{c}$  + jets and  $Wc$  + jets) and  $W$  + light jets, are taken from samples of simulated events, while the normalisation of the flavour composition is derived from data. The NN analysis simultaneously determines the normalisation of the  $W$  + light jets and  $W$  + heavy flavour processes when fitting the NN discriminant distribution to measure the  $t$ -channel single top-quark rate. The cut-based analysis derives normalisation factors for the  $W$  + jets processes using the event yields in the 1-jet  $b$ -tagged, 2-jet pretag, and 2-jet  $b$ -tagged sample, excluding events selected by the cuts defined in Section 5.2. Since the 2-jet  $b$ -tagged sample includes some  $t$ -channel signal events, despite requiring that the events fail the selection of the cut-based analysis, an uncertainty of 100% on the expected  $t$ -channel single top-quark rate is assumed in this normalisation procedure. Both estimates of the  $W$  + jets backgrounds, the one of the NN analysis and the one of the cut-based analysis, are in very good agreement with each other.

The predicted and observed event yields, after the application of the selections described in Section 3, are given in Table 1, separately for the electron and muon channels, in the 2-jet and 3-jet  $b$ -tagged samples. For the purpose of this table and the histograms of kinematic distributions the contributions of the  $t\bar{t}$ ,  $Wt$  and  $s$ -channel processes have been grouped together into one category called “ $t\bar{t}$ , other top”. In the subsequent analysis the electron and muon channels are combined.

## 5. Signal and background discrimination

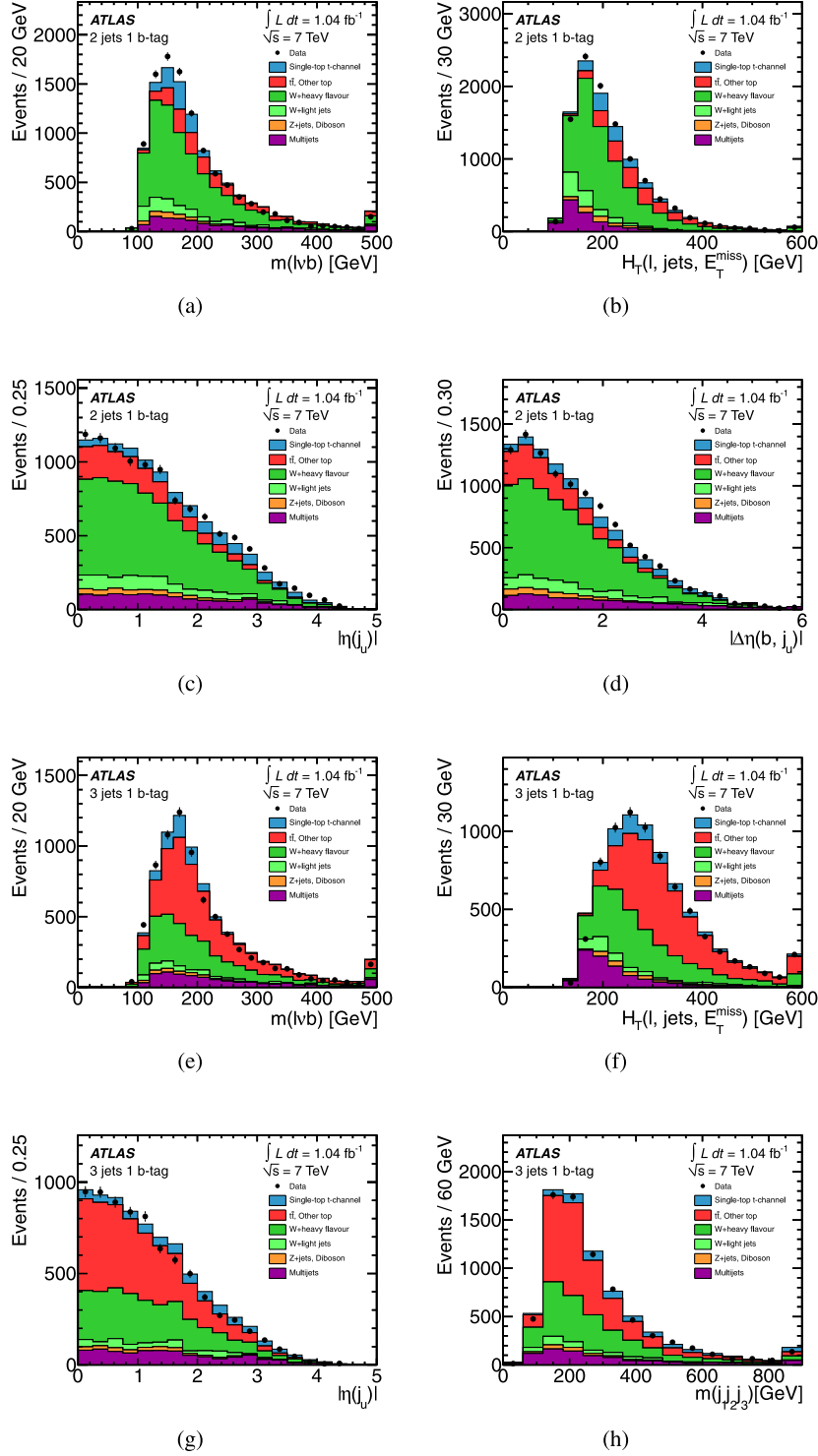
To separate  $t$ -channel single top-quark signal events from background several kinematic variables are combined into one discriminant by employing an NN, that also exploits correlations between the variables. The result of the NN analysis is corroborated by a

cut-based analysis that applies additional criteria to the basic selection described in Section 3.

### 5.1. Neural network based discriminant

The NeuroBayes [40,41] tool (version 3.3) is used for preprocessing the input variables and for the training of the NN. A large number of input variables is studied, but only the highest-ranking variables are chosen for the training of the NN. The ranking of variables is automatically determined as part of the preprocessing step and is independent of the training procedure. The total correlation  $\kappa_t^{\text{total}}$  of a set of variables to the target function, that assumes the value 1 for signal and 0 for background events, is computed as a measure of the discrimination power of these variables. In an iterative procedure, the variables are sorted according to the loss in  $\kappa_t^{\text{total}}$  that is induced due to their removal from the set. Considering the number of simulated events used to determine the ranking, one can compute the significance of the information loss caused by the removal of a certain variable. For the training of the NN we use only variables that contribute with more than 20 (10) standard deviations to  $\kappa_t^{\text{total}}$  in the 2-jet (3-jet) data set. This choice is a compromise between the achievable discrimination power, that increases with the number of variables, and the practical aim of keeping the number of variables at a manageable level.

As a result of this optimisation procedure 12 kinematic variables are identified that serve as inputs to the NN in the 2-jet data set. The most discriminating variable is the invariant mass of the  $b$ -tagged jet, the charged lepton, and the neutrino,  $m(\ell\nu b)$ , which is an estimator for the top-quark mass for signal events. In this calculation the transverse momentum of the neutrino is given by the  $x$ - and  $y$ -components of the  $E_T^{\text{miss}}$  vector, while the unmeasured  $z$ -component of the neutrino momentum,  $p_z(\nu)$ , is inferred by imposing a  $W$ -boson mass constraint on the lepton–neutrino system. Since the constraint leads to a quadratic equation for  $p_z(\nu)$ , a two-fold ambiguity arises. In the case of two real solutions, the one with the smaller  $|p_z|$  is chosen. If the solutions are complex, those are avoided by a kinematic fit that rescales the neutrino  $p_x$  and  $p_y$  such that the imaginary radical vanishes, but keeps the transverse components of the neutrino as close as possible to the  $E_T^{\text{miss}}$ . The second and third most discriminating variables are the absolute value of the pseudorapidity of the highest  $p_T$  untagged jet  $|\eta(j_u)|$  and the transverse energy of the untagged jet  $E_T(j_u)$ . Other variables used by the NN in the 2-jet data set are: the absolute value of  $\Delta\eta$  between the  $b$ -tagged jet and the reconstructed  $W$  boson  $|\Delta\eta(b, W)|$ ; the absolute value of  $\Delta\eta$  between the  $b$ -tagged jet and the highest  $p_T$  untagged jet  $|\Delta\eta(b, j_u)|$ ; the transverse momentum of the charged lepton  $p_T(\ell)$ ; the scalar sum of the transverse momenta of the lepton,

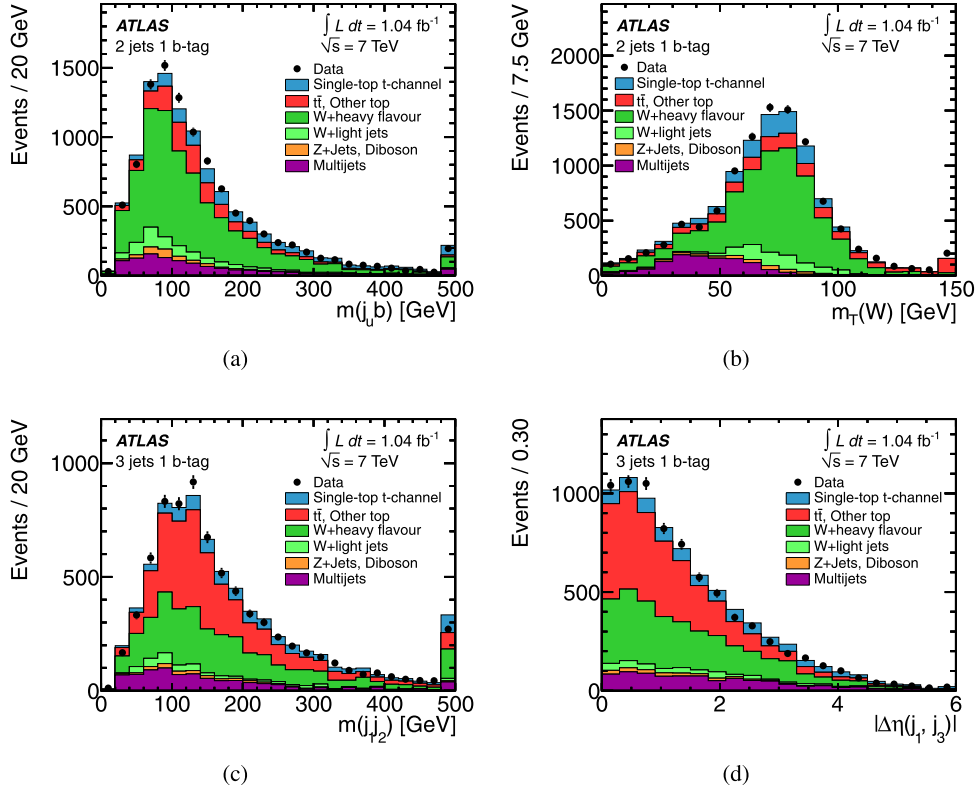


**Fig. 1.** Discriminating variables in the  $b$ -tagged sample for 2-jet events and 3-jet events. Multijet event yields are determined with a data-driven technique. Contributions from  $W + \text{jets}$  events are derived from simulation and normalised to data in control regions with the method employed in the cut-based analysis. All other backgrounds and the  $t$ -channel signal expectation are normalised to theoretical cross sections. The last histogram bin includes overflows. The figures shown are for 2-jet or 3-jet events, respectively: (a), (e) the invariant mass of the  $b$ -tagged jet, the charged lepton, and the neutrino; (b), (f) the scalar sum of the transverse momenta of the lepton, the jets, and  $E_T^{\text{miss}}$ ; (c), (g) the absolute value of the pseudorapidity of the highest  $p_T$  untagged jet. For 2-jet events figure (d) shows the absolute value of  $\Delta\eta$  between the  $b$ -tagged jet and the highest  $p_T$  untagged jet; and for 3-jet events figure (h) displays the invariant mass of the three selected jets.

jets, and  $E_T^{\text{miss}}$ ,  $H_T(\ell, \text{jets}, E_T^{\text{miss}})$ ;  $m_T(W)$ ; the pseudorapidity of the lepton  $\eta(\ell)$ ; the invariant mass of the  $b$ -tagged jet  $m(b)$ ;  $E_T^{\text{miss}}$ ; and the invariant mass of the untagged jet and the  $b$ -tagged jet  $m(j_U b)$ .

For events with three jets 18 variables are used, the most discriminating ones being the invariant mass of the two leading jets,  $m(j_1 j_2)$ ,  $m(\ell \nu b)$ , and the absolute value of the difference in the pseudorapidity of the leading and lowest  $p_T$  jet,  $|\Delta\eta(j_1, j_3)|$ . Fig. 1





**Fig. 2.** Additional discriminating variables used in the NN analysis for 2-jet and 3-jet events. The rate of multijet events is normalised to the estimate obtained from the fit to the  $E_T^{\text{miss}}$  distributions. All other component distributions are normalised to the result of the maximum-likelihood fit of the NN output. The last histogram bin includes overflows. The figures shown are, for 2-jet events: (a) invariant mass of the highest  $p_T$  untagged jet and the  $b$ -tagged jet; (b) transverse mass of the lepton- $E_T^{\text{miss}}$  system; and for 3-jet events: (c) invariant mass of the two leading jets; (d) absolute value of  $\Delta\eta$  between the leading jet and the lowest  $p_T$  jet.

shows distributions of some of the most discriminating variables in the  $b$ -tagged 2-jet or 3-jet samples, used in both the NN analysis and the cut-based analysis. The variable  $m(j_1 j_2 j_3)$  denotes the invariant mass of all selected jets in the 3-jet data set. Distributions of additional variables used only in the NN approach are shown in Fig. 2.

The agreement between the background model and collision data is tested in the large pretag sample for each input variable used in the analysis, for various additional control variables, and the NN output distributions, which are shown in Figs. 3(a) and 3(b). In this control sample, where the  $b$ -tagging algorithm has not yet been applied, the  $b$ -tagged jet is substituted by the most central jet, with the requirement that it is within  $|\eta| < 2.5$ . Good agreement is found overall, except for the  $|\eta|$  distribution of the jet with the highest  $|\eta|$  in the pretag data set for which an additional systematic modelling uncertainty is taken into account (see Section 6).

The NeuroBayes tool combines a three-layer feed-forward NN with a complex preprocessing of the input variables. By transforming the variables in the preprocessing step the influence of outliers is largely reduced and statistical fluctuations are damped. NeuroBayes applies Bayesian regularisation techniques for the training process to damp statistical fluctuations in the training sample and to avoid overtraining. A certain fraction of simulated events (20%) is not included in the training sample and is used as an independent test sample to check that there is no overtraining. The ratio of signal to background events in the training is chosen to be 1:1, while the different background processes are weighted according to the number of expected events.

To extract the signal content of the selected sample a maximum-likelihood fit is performed to the complete NN output dis-

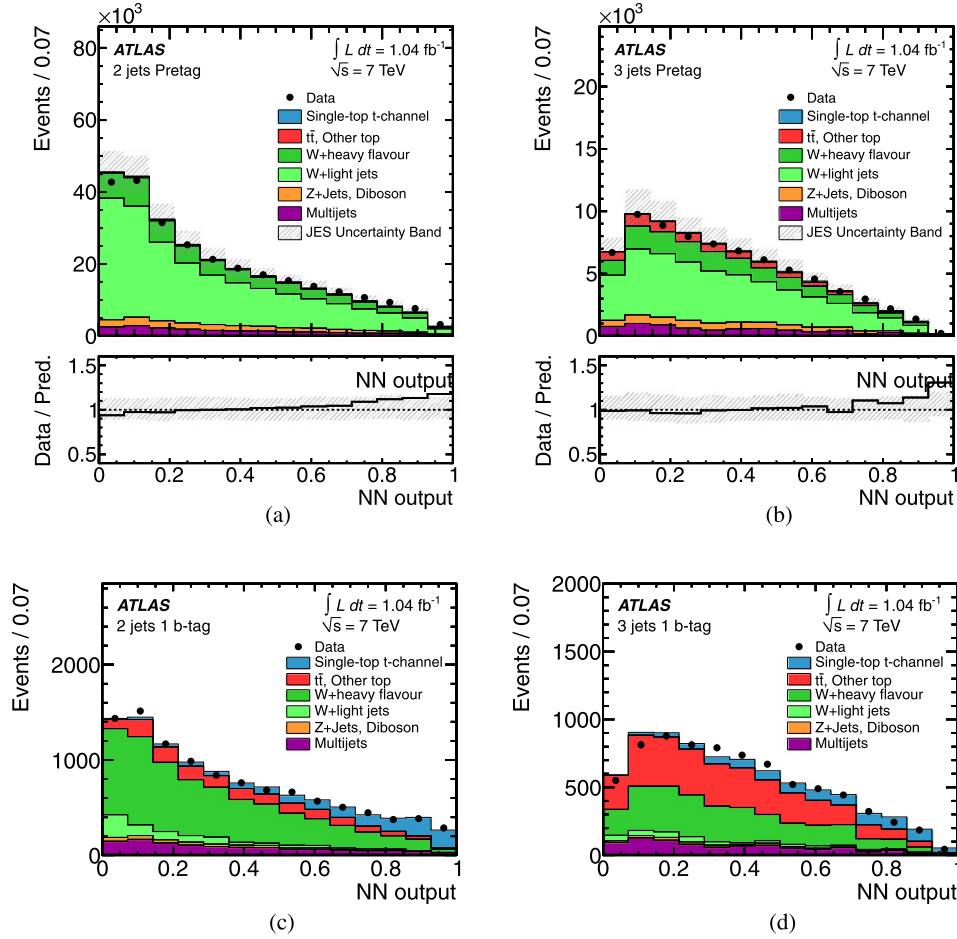
tributions in the 2-jet and 3-jet data sets (see Section 7). Fitting all bins of the distribution has the advantage of making maximal use of the signal events remaining after the event selection, and also allows the background rates to be constrained by the data. The sensitivity to the background rates is given by the background dominated region close to zero. The observed NN output distributions scaled to the fit result are shown in Figs. 3(c) and 3(d) for  $b$ -tagged events with two or three jets, respectively.

## 5.2. Cut-based selection

In the cut-based analysis additional selections are applied to a subset of five variables used by the NN analysis:  $|\eta(j_u)| > 2$ ,  $H_T(\ell, \text{jets}, E_T^{\text{miss}}) > 210$  GeV, and  $150 \text{ GeV} < m(\ell\nu b) < 190$  GeV. The 2-jet selection requires  $|\Delta\eta(b, j_u)| > 1$ , while the 3-jet selection requires that  $m(j_1 j_2 j_3)$  is higher than 450 GeV, to further reduce the large  $t\bar{t}$  contribution in this channel. The selection cuts were chosen in order to increase the expected significance of the  $t$ -channel single top-quark signal, taking into account systematic uncertainties on the background estimate [42].

The positive and negative lepton-charge samples are considered separately, as more single-top quark  $t$ -channel events are expected in the  $e^+/\mu^+$  samples than in the  $e^-/\mu^-$  samples due to the dominance of valence  $u$  quarks in the proton over  $d$  quarks. The 2-jet and 3-jet data sets are also considered separately.

The signal and background event counts for the positive and negative lepton-charge samples are given in Table 2. The observed event yields are consistent with the SM expectation in each channel. Fig. 4(a) shows the distribution of the lepton charge for events with two or three jets after the application of all cut-based selections. Figs. 4(b) and 4(c) display the variable  $m(\ell\nu b)$  for 2-jet



**Fig. 3.** (a) and (b) Neural network output distribution for the pretag sample, including the JES uncertainty on the prediction (hatched region). The multijet component is normalised to the estimate obtained from the fit to the  $E_T^{\text{miss}}$  distributions. All other components are normalised such that the total number of expected events in the pretag sample is equal to the observed number of events. The ratio between the data and the total predicted distributions is also shown. (c) and (d) NN output distribution for the 2-jet and 3-jet  $b$ -tagged samples, respectively. All component distributions are normalised to the result of the maximum-likelihood fit, except for the component of multijet events that is normalised to the estimate obtained from the fit to the  $E_T^{\text{miss}}$  distributions.

and 3-jet events respectively after applying all selections except for the cut on  $m(\ell\nu b)$ . In these figures, the  $t$ -channel single top-quark contribution is normalised to the observed cross section as measured from the combination of all four channels.

## 6. Systematic uncertainties

Systematic uncertainties on the normalisation of the individual backgrounds and on the signal acceptance affect the measured single top-quark  $t$ -channel cross section. In the NN analysis the shape of each individual prediction is also affected; both the rate and the shape uncertainties are taken into account by generating correlated pseudo-experiments. The impact of the systematic uncertainties on the  $t$ -channel cross section measurement is estimated from these pseudo-experiments. The uncertainties can be split into the following categories:

### 6.1. Object modelling

Systematic uncertainties due to the residual differences between data and Monte Carlo simulation for the reconstruction and energy calibration of jets, electrons and muons are propagated in the analysis. The main source of object modelling uncertainty comes from the jet energy scale (JES), including the modelling of pile-up, as well as  $b$ -jet identification. Other components include

lepton energy scale and lepton and jet identification efficiencies. The JES uncertainty has been evaluated using 2010 data [31]. Additional contributions to this uncertainty due to the larger pile-up effects in 2011 data are included and range from less than 1% to 5% as a function of jet  $p_T$  and  $\eta$ . For  $b$ -quark jets a JES uncertainty of 0.8% to 2.5%, depending on the jet  $p_T$ , is added in quadrature to the JES uncertainty. Scale factors, determined from collision data [32], are applied to correct the  $b$ -tagging performance in simulated events to match the data. Both  $b$ -jets and  $c$ -jets in simulation use the same  $b$ -tagging scale factors with uncertainties that depend on the  $p_T$  and  $\eta$  of the jet. The uncertainties on the scale factors vary from 10% to 15% for  $b$ -quark jets and from 20% to 30% for  $c$ -quark jets. For light-quark jets the mis-tagging uncertainty ranges from 20% to 50% as a function of jet  $p_T$  and  $\eta$ . Other minor uncertainties are assigned to the reconstruction of  $E_T^{\text{miss}}$  and to account for the impact of pile-up collisions on  $E_T^{\text{miss}}$ . Finally, a systematic uncertainty was also assigned to account for temporary failures of parts of the LAr calorimeter readout during part of the data-taking period, which was not modelled in the MC samples.

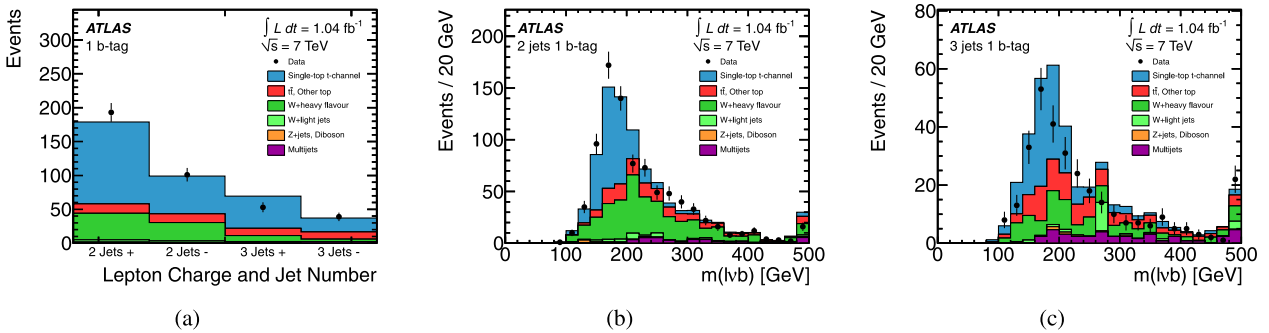
### 6.2. Monte Carlo generators and PDFs

Systematic uncertainties arising from the modelling of the single top-quark signal and the  $t\bar{t}$  background are taken into account. The largest contributions come from the modelling of parton

**Table 2**

Event yield for the 2-jet and 3-jet  $b$ -tagged positive and negative lepton-charge channels after the cut-based selection. The multijet and  $W + \text{jets}$  backgrounds are normalised to observed data in control regions, all other samples are normalised to theory cross sections. Uncertainties shown include all sources of systematic errors, summed quadratically and without taking into account possible anticorrelations between systematic sources and between processes.

	Cut-based 2-jet		Cut-based 3-jet	
	Lepton +	Lepton –	Lepton +	Lepton –
Single-top $t$ -channel	$85 \pm 29$	$39 \pm 13$	$33.6 \pm 7.0$	$14.6 \pm 6.2$
$t\bar{t}$ , other top	$14.0 \pm 6.4$	$12.8 \pm 4.2$	$10.5 \pm 4.2$	$10.7 \pm 7.9$
$W + \text{light jets}$	$3.3 \pm 1.9$	$2.0 \pm 1.2$	$0.8 \pm 1.3$	$0.3 \pm 0.3$
$W + \text{heavy flavour jets}$	$39 \pm 11$	$27.1 \pm 7.5$	$8.7 \pm 6.0$	$3.4 \pm 3.1$
$Z + \text{jets, diboson}$	$1.1 \pm 0.8$	$1.0 \pm 0.8$	$0.3 \pm 0.2$	$0.2 \pm 0.3$
Multijet	$0.2 \pm 0.2$	$0.3 \pm 0.3$	$1.5 \pm 1.1$	$3.1 \pm 2.0$
Total expected	$143 \pm 31$	$83 \pm 16$	$56 \pm 10$	$32 \pm 11$
S/B	1.5	0.9	1.6	1.0
Data	193	101	53	39



**Fig. 4.** (a) Distribution of the lepton charge after the full cut-based selection for 2-jet and 3-jet events. (b), (c) Invariant mass of the  $b$ -tagged jet, the charged lepton, and the neutrino,  $m(l\nu b)$ , for the  $b$ -tagged sample for 2-jet (b) and 3-jet (c) events after applying all cut-based selections except for the cut on  $m(l\nu b)$ . In all three distributions the  $t$ -channel single top-quark contribution is normalised to the observed cross section obtained with the cut-based analysis. The last histogram bin includes overflows.

showers and hadronisation, estimated by interchanging the modelling between PYTHIA and HERWIG, and from the amount of initial-state and final-state radiation (ISR/FSR), estimated using dedicated ACERMC samples interfaced to PYTHIA where parameters controlling the ISR/FSR emission are varied in a range<sup>3</sup> consistent with those used in the Perugia Hard/Soft tune variations [43]. The uncertainty due to the choice of the single top-quark  $t$ -channel signal generator is estimated from the difference between ACERMC and MCFM predictions [44]. The modelling uncertainty for the  $t\bar{t}$  background is evaluated by comparing the generators MC@NLO and POWHEG [45,46] (with HERWIG showering). For the  $W + \text{jets}$  background a shape uncertainty is assigned based on the variation of the choices of the matching scale and of the functional form of the factorisation scale in ALPGEN. Systematic uncertainties related to the parton distribution functions are taken into account for the signal and for all background processes which are modelled by simulated events. In addition to the nominal PDF set the alternative MSTW2008NLO68CL [47] and CTEQ6.6 PDF sets are investigated. Events are reweighted according to each of the PDF uncertainty eigenvectors and the total uncertainty is evaluated following the procedure described in Ref. [36]. An additional uncertainty is assigned for the mis-modelling of jets in the forward  $|\eta|$  regions. A weight function is derived from the pretag sample by

dividing the observed  $|\eta|$  distribution in data by the distribution obtained from simulated events, for 2-jet and 3-jet events. The event weights defined in this way are then applied to all simulated samples in the  $b$ -tagged data set. The systematic uncertainty is derived from the one-sided difference between the weighted and the nominal samples. The impact of using simulation samples of limited size is also taken into account.

### 6.3. Theoretical cross section normalisation

The  $t\bar{t}$ , single-top quark  $Wt$ - and  $s$ -channel backgrounds are normalised to their theory predictions with theoretical uncertainties of  $^{+7}_{-10}\%$ , 7% and 4%, respectively [48,10,11]. The uncertainty on the diboson background is 5% [38].

### 6.4. Background normalisation to data

The multijet background estimate has an uncertainty of 50%. The NN analysis places an uncertainty of 50% on the rate of events with  $W + \text{heavy flavour jets}$  and 30% on the rate of  $W + \text{light jets}$  events. These uncertainties are used as constraints on the predictions when simultaneously determining the  $W + \text{jets}$  rates and the signal cross section. The cut-based analysis does not apply a global uncertainty on the  $W + \text{heavy flavour}$  and  $W + \text{light flavour}$  rates, but considers separately the impact of the dominant sources of uncertainty on the data-derived  $W + \text{jets}$  normalisation factors. This treatment allows the correlation between each component of uncertainty on the normalisation factors and the uncertainties on the  $W + \text{jets}$  rates to be taken into account. The  $Z + \text{jets}$  background normalisation has an uncertainty of 60%.

<sup>3</sup> The default PYTHIA values of these parameters are:  $\text{PARP}(67) = 4.0$  and  $\text{PARP}(64) = 1.0$  for ISR and  $\text{PARP}(72) = 0.192$  GeV,  $\text{PARJ}(82) = 1.0$  GeV for FSR. To decrease (increase) ISR, the parameters  $\text{PARP}(67)$  and  $\text{PARP}(64)$  are set to 0.5 and 4.0 (6.0 and 0.25), respectively. To decrease (increase) FSR, the parameters  $\text{PARP}(72)$  and  $\text{PARJ}(82)$  are set to 0.096 GeV and 2.0 GeV (0.384 GeV and 0.5 GeV), respectively. Samples of simulated events are produced with six different sets of parameters settings: ISR increased (decreased), FSR increased (decreased), and a simultaneous increase (decrease) of ISR and FSR.



**Table 3**

Breakdown of the contribution of each source of uncertainty to the total uncertainty of the measured  $t$ -channel cross section in data for the NN analysis and the cut-based analysis. Theoretical uncertainties are included in the “Other backgrounds” uncertainty category.

Source	$\Delta\sigma_{\text{obs}}/\sigma_{\text{obs}} [\%]$	
	NN	Cut-based
Data statistics	$\pm 5$	$\pm 8$
Object modelling		
Jets	$\pm 6$	$+3/-4$
$b$ -tagging efficiency	$\pm 13$	$\pm 12$
Mistagging rate	$\pm 1$	$\pm 1$
Lepton	$\pm 2$	$\pm 4$
$E_T^{\text{miss}}$ , calorimeter readout	$\pm 2$	$\pm 2$
Monte Carlo		
PDF	$\pm 3$	$\pm 4$
Generator	$\pm 4$	$\pm 7$
Parton shower	$\pm 5$	$\pm 11$
ISR/FSR	$\pm 14$	$+19/-18$
Forward jet modelling	$+6/-4$	$+7/-5$
MC statistics	$\pm 3$	$\pm 4$
Background normalisation		
Multijets	$\pm 4$	$\pm 2$
Other backgrounds	$\pm 1$	$\pm 6$
Luminosity	$\pm 4$	$\pm 4$
Total systematic uncertainties	$+24/-23$	$+30/-27$
Total uncertainty	$\pm 24$	$+31/-28$

### 6.5. Luminosity

The uncertainty on the integrated luminosity is 3.7% [13,14].

Table 3 shows the contribution of each source of uncertainty to the total uncertainty on the measured  $t$ -channel cross section ( $\Delta\sigma_{\text{obs}}/\sigma_{\text{obs}}$ ) for the neural network analysis and for the cut-based analysis.

## 7. Cross section measurements

Both the cut-based and neural network analyses employ a maximum-likelihood fit method to measure the single top-quark  $t$ -channel cross section. The general likelihood function is given by the product of the Poisson likelihoods in the individual channels. The background rates are constrained by Gaussian priors. We use the following equations:

$$L(\beta^s; \beta_j^b) = \prod_{k=1}^M \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!} \cdot \prod_{j=1}^B G(\beta_j^b; 1, \Delta_j) \quad \text{with}$$

$$\mu_k = \mu_k^s + \sum_{j=1}^B \mu_{jk}^b, \quad \mu_k^s = \beta^s \cdot \tilde{v}_s \cdot \alpha_k^s, \quad \text{and}$$

$$\mu_{jk}^b = \beta_j^b \cdot \tilde{v}_j \cdot \alpha_{jk},$$

where  $M$  is the number of channels and  $B$  the number of background processes. The cut-based analysis uses  $M = 4$  channels separated by lepton charge and the number of jets, while in the NN-based analysis  $M$  is equal to 28, namely the number of bins of the NN discriminant in the 2-jet channel plus the number of bins of the NN discriminant in the 3-jet channel. Here  $\tilde{v}_s$  and  $\tilde{v}_j$  are, respectively, the predicted number of signal events and the number of events of background  $j$  in the selected data set. The number of observed (expected) events in channel  $k$  is denoted by  $n_k$  ( $\mu_k$ ). The expected number of events in channel  $k$  is  $\mu_k^s$  for the signal and  $\mu_{jk}^b$  for each background  $j$ . The fraction of events falling in channel  $k$  is given by  $\alpha_k^s$  and  $\alpha_{jk}$  for signal and background

respectively. For the NN-based analysis the sets of  $\alpha_k^s$  and  $\alpha_{jk}$  constitute the probability densities (shapes) of the NN discriminants. The scale factors  $\beta^s$  for signal and  $\beta_j^b$  for the backgrounds are the parameters of the likelihood function that are fitted to the data. The Gaussian constraints on the background scale factors,  $\Delta_j$ , are set to the theoretical cross section uncertainty for all background processes that do not use data-based estimates ( $t\bar{t}$ ,  $Wt$ ,  $s$ -channel and diboson), while  $W$  + jets backgrounds are constrained within their data-derived uncertainties. The multijet background is fixed to the value estimated from data.

The systematic uncertainties on the cross section measurement are determined using a frequentist method based on a large number of pseudo-experiments. For each pseudo-experiment the expectation values of the backgrounds  $\tilde{v}_j$  and of the signal  $\tilde{v}_s$  as well as the relative distribution of events across the channels ( $\alpha_k^s$  and  $\alpha_{jk}$ ) are varied including all sources of uncertainties described in Section 6 and the  $t$ -channel cross section is measured with the maximum-likelihood fit. The distribution of measured cross sections is an estimator of the probability density function of all possible outcomes of the measurement and it is used to estimate the uncertainty on the actual measurement.

The NN-based analysis yields, from a simultaneous measurement in the 2-jet and 3-jet channels, a cross section of

$$\sigma_t = 83 \pm 4 \text{ (stat.)}_{-19}^{+20} \text{ (syst.) pb} = 83 \pm 20 \text{ pb.}$$

The significance of the observed signal corresponds to 7.2 standard deviations (6.0 expected). This is computed using as a test statistic the  $Q$ -value, which is defined as the ratio of the value of the likelihood function maximised for the Standard Model signal cross section to the value of the likelihood function maximised for zero signal.

The cut-based analysis measures, by combining four different channels (positive and negative lepton charge, with two and three jets) a cross section of  $\sigma_t = 92_{-26}^{+29}$  pb, in good agreement with the NN-based measurement. The separation of candidate events according to the lepton charge allows individual measurements of the top-quark and top-antiquark cross sections, yielding the results  $\sigma(t) = 59_{-16}^{+18}$  pb and  $\sigma(\bar{t}) = 33_{-12}^{+13}$  pb, that can be compared to the theoretically predicted cross sections of  $41.9_{-0.8}^{+1.8}$  pb and  $22.7_{-1.0}^{+0.9}$  pb, respectively [9].

To test the compatibility, the two measurements from the NN-based and cut-based analyses are combined using the Best Linear Unbiased Estimator (BLUE) method [49]. The correlation coefficient of the two analyses is 75% and was determined with ensemble tests including all systematic uncertainties. Based on the ensemble tests the two results are found to be compatible within one standard deviation. However, the combined result and its uncertainty for the observed cross section measurement does not significantly differ from the result obtained with the NN analysis alone.

## 8. $V_{tb}$ measurement

Single top-quark production in the  $t$ -channel proceeds via a  $W$ - $t$ - $b$  vertex and the measured cross section is proportional to  $|V_{tb}|^2$ , where  $V_{tb}$  is the relevant CKM matrix element. In the Standard Model  $|V_{tb}|$  is close to one, but new physics contributions could alter its value significantly.

The  $|V_{tb}|$  measurement is independent of assumptions about the number of quark generations or about the unitarity of the CKM matrix. The only assumptions required are that  $|V_{tb}| \gg |V_{td}|, |V_{ts}|$  and that the  $W$ - $t$ - $b$  interaction is an SM-like left-handed weak coupling. Therefore, the  $t\bar{t}$  background rate is unaffected by a variation of  $|V_{tb}|$  since decays to a potential higher generation are prohibited by kinematics. On the other hand, rates of single-top

quark  $Wt$  and  $s$ -channel backgrounds also scale with  $|V_{tb}|^2$ , but their contributions are small in the signal region that drives the maximum-likelihood fit measurement. The resulting variation on the total top-quark background yield is less than its systematic uncertainty and thus considered negligible.

The value of  $|V_{tb}|^2$  is extracted by dividing the observed single top-quark  $t$ -channel cross section, measured using the NN method, by the SM expectation [9]. The experimental and theoretical uncertainties are added in quadrature. The result obtained is  $|V_{tb}| = 1.13_{-0.13}^{+0.14} (\text{exp.}) \pm 0.02 (\text{theo.}) = 1.13_{-0.13}^{+0.14}$ . Restricting the range of  $|V_{tb}|$  to the interval  $[0, 1]$ , as required by the SM, a lower limit on  $|V_{tb}|$  is extracted:  $|V_{tb}| > 0.75$  at the 95% confidence level.

## 9. Conclusion

In summary, we present a measurement of the cross section of single top-quark production in the  $t$ -channel with the ATLAS detector in  $pp$  collisions at  $\sqrt{s} = 7$  TeV. The measurement is based on a neural network discriminant separating signal events from background and yields a cross section of  $83 \pm 20$  pb. The corresponding coupling at the  $W$ - $t$ - $b$  vertex is  $|V_{tb}| = 1.13_{-0.13}^{+0.14}$  and the 95% confidence level lower limit on the CKM matrix element  $|V_{tb}|$  is 0.75.

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Amaral<sup>29</sup>, C. Amelung<sup>22</sup>, V.V. Ammosov<sup>127</sup>, A. Amorim<sup>123a,b</sup>, G. Amorós<sup>166</sup>, N. Amram<sup>152</sup>, C. Anastopoulos<sup>29</sup>, L.S. Ancu<sup>16</sup>, N. Andari<sup>114</sup>, T. Andeen<sup>34</sup>, C.F. Anders<sup>20</sup>, G. Anders<sup>58a</sup>, K.J. Anderson<sup>30</sup>, A. Andreazza<sup>88a,88b</sup>, V. Andrei<sup>58a</sup>, M.-L. Andrieux<sup>55</sup>, X.S. Anduaga<sup>69</sup>, A. Angerami<sup>34</sup>, F. Anghinolfi<sup>29</sup>, A. Anisenkov<sup>106</sup>, N. Anjos<sup>123a</sup>, A. Annovi<sup>47</sup>, A. Antonaki<sup>8</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>95</sup>, J. Antos<sup>143b</sup>, F. Anulli<sup>131a</sup>, S. Aoun<sup>82</sup>, L. Aperio Bella<sup>4</sup>, R. Apolle<sup>117,c</sup>, G. Arabidze<sup>87</sup>, I. Aracena<sup>142</sup>, Y. Arai<sup>65</sup>, A.T.H. Arce<sup>44</sup>, S. Arfaoui<sup>147</sup>, J.-F. Arguin<sup>14</sup>, E. Arik<sup>18a,\*</sup>, M. Arik<sup>18a</sup>, A.J. Armbruster<sup>86</sup>, O. Arnaez<sup>80</sup>, V. Arnal<sup>79</sup>, C. Arnault<sup>114</sup>, A. Artamonov<sup>94</sup>, G. Artoni<sup>131a,131b</sup>, D. Arutinov<sup>20</sup>, S. Asai<sup>154</sup>, R. Asfandiyarov<sup>171</sup>, S. Ask<sup>27</sup>, B. Åsman<sup>145a,145b</sup>, L. Asquith<sup>5</sup>, K. Assamagan<sup>24</sup>, A. Astbury<sup>168</sup>, A. Astvatsatourov<sup>52</sup>, B. Aubert<sup>4</sup>, E. Auge<sup>114</sup>, K. Augsten<sup>126</sup>, M. Aurousseau<sup>144a</sup>, G. Avolio<sup>162</sup>, R. Avramidou<sup>9</sup>, D. Axen<sup>167</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>92,d</sup>, Y. Azuma<sup>154</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>88a</sup>, C. Bacci<sup>133a,133b</sup>, A.M. Bach<sup>14</sup>, H. Bachacou<sup>135</sup>, K. Bachas<sup>29</sup>, M. Backes<sup>49</sup>, M. Backhaus<sup>20</sup>, E. Badescu<sup>25a</sup>, P. Bagnaia<sup>131a,131b</sup>, S. Bahinipati<sup>2</sup>, Y. Bai<sup>32a</sup>, D.C. Bailey<sup>157</sup>, T. Bain<sup>157</sup>, J.T. Baines<sup>128</sup>, O.K. Baker<sup>174</sup>, M.D. Baker<sup>24</sup>, S. Baker<sup>76</sup>, E. Banas<sup>38</sup>, P. Banerjee<sup>92</sup>, Sw. Banerjee<sup>171</sup>, D. Banfi<sup>29</sup>, A. Bangert<sup>149</sup>, V. Bansal<sup>168</sup>, H.S. Bansil<sup>17</sup>, L. Barak<sup>170</sup>, S.P. Baranov<sup>93</sup>, A. Barashkou<sup>64</sup>, A. Barbaro Galtieri<sup>14</sup>, T. Barber<sup>48</sup>, E.L. Barberio<sup>85</sup>, D. Barberis<sup>50a,50b</sup>, M. Barbero<sup>20</sup>, D.Y. Bardin<sup>64</sup>, T. Barillari<sup>98</sup>, M. Barisonzi<sup>173</sup>, T. Barklow<sup>142</sup>, N. Barlow<sup>27</sup>, B.M. Barnett<sup>128</sup>, R.M. Barnett<sup>14</sup>, A. Baroncelli<sup>133a</sup>, G. Barone<sup>49</sup>, A.J. Barr<sup>117</sup>, F. Barreiro<sup>79</sup>, J. Barreiro Guimarães da Costa<sup>57</sup>, P. Barrillon<sup>114</sup>, R. Bartoldus<sup>142</sup>, A.E. Barton<sup>70</sup>, V. Bartsch<sup>148</sup>, R.L. Bates<sup>53</sup>, L. Batkova<sup>143a</sup>, J.R. Batley<sup>27</sup>, A. Battaglia<sup>16</sup>, M. Battistin<sup>29</sup>, F. Bauer<sup>135</sup>, H.S. Bawa<sup>142,e</sup>, S. Beale<sup>97</sup>, T. Beau<sup>77</sup>, P.H. Beauchemin<sup>160</sup>, R. Beccherle<sup>50a</sup>, P. Bechtel<sup>20</sup>, H.P. Beck<sup>16</sup>, S. Becker<sup>97</sup>, M. Beckingham<sup>137</sup>, K.H. Becks<sup>173</sup>, A.J. Beddall<sup>18c</sup>, A. Beddall<sup>18c</sup>, S. Bedikian<sup>174</sup>, V.A. Bednyakov<sup>64</sup>, C.P. Bee<sup>82</sup>, M. Begel<sup>24</sup>, S. Behar Harpaz<sup>151</sup>, P.K. Behera<sup>62</sup>, M. Beimforde<sup>98</sup>, C. Belanger-Champagne<sup>84</sup>, P.J. Bell<sup>49</sup>, W.H. Bell<sup>49</sup>, G. Bella<sup>152</sup>, L. Bellagamba<sup>19a</sup>, F. Bellina<sup>29</sup>, M. Bellomo<sup>29</sup>, A. Belloni<sup>57</sup>, O. Beloborodova<sup>106,f</sup>, K. Belotskiy<sup>95</sup>, O. Beltramello<sup>29</sup>, O. Benary<sup>152</sup>, D. Bencheikroun<sup>134a</sup>, M. Bendel<sup>80</sup>, N. Benekos<sup>164</sup>, Y. Benhammou<sup>152</sup>, E. Benhar Nocchioli<sup>49</sup>, J.A. Benitez Garcia<sup>158b</sup>, D.P. Benjamin<sup>44</sup>, M. Benoit<sup>114</sup>, J.R. Bensinger<sup>22</sup>, K. Benslama<sup>129</sup>, S. Bentvelsen<sup>104</sup>, D. Berge<sup>29</sup>, E. Bergeaas Kuutmann<sup>41</sup>, N. Berger<sup>4</sup>, F. Berghaus<sup>168</sup>, E. Berglund<sup>104</sup>, J. Beringer<sup>14</sup>, P. Bernat<sup>76</sup>, R. Bernhard<sup>48</sup>, C. Bernius<sup>24</sup>, T. Berry<sup>75</sup>, C. Bertella<sup>82</sup>, A. Bertin<sup>19a,19b</sup>, F. Bertinelli<sup>29</sup>, F. Bertolucci<sup>121a,121b</sup>, M.I. Besana<sup>88a,88b</sup>, N. Besson<sup>135</sup>, S. Bethke<sup>98</sup>, W. Bhimji<sup>45</sup>, R.M. Bianchi<sup>29</sup>, M. Bianco<sup>71a,71b</sup>, O. Biebel<sup>97</sup>, S.P. Bieniek<sup>76</sup>, K. Bierwagen<sup>54</sup>, J. Biesiada<sup>14</sup>, M. Biglietti<sup>133a</sup>, H. Bilokon<sup>47</sup>, M. Bindi<sup>19a,19b</sup>, S. Binet<sup>114</sup>, A. Bingul<sup>18c</sup>, C. Bini<sup>131a,131b</sup>, C. Biscarat<sup>176</sup>, U. Bitenc<sup>48</sup>, K.M. Black<sup>21</sup>, R.E. Blair<sup>5</sup>, J.-B. Blanchard<sup>135</sup>, G. Blanchot<sup>29</sup>, T. Blazek<sup>143a</sup>, C. Blocker<sup>22</sup>, J. Blocki<sup>38</sup>, A. Blondel<sup>49</sup>, W. Blum<sup>80</sup>, U. Blumenschein<sup>54</sup>, G.J. Bobbink<sup>104</sup>, V.B. Bobrovnikov<sup>106</sup>, S.S. Bocchetta<sup>78</sup>, A. Bocci<sup>44</sup>, C.R. Boddy<sup>117</sup>, M. Boehler<sup>41</sup>, J. Boek<sup>173</sup>, N. Boelaert<sup>35</sup>, J.A. Bogaerts<sup>29</sup>, A. Bogdanchikov<sup>106</sup>, A. Bogouch<sup>89,\*</sup>, C. Bohm<sup>145a</sup>, J. Bohm<sup>124</sup>, V. Boisvert<sup>75</sup>, T. Bold<sup>37</sup>, V. Boldea<sup>25a</sup>, N.M. Bolnet<sup>135</sup>, M. Bomben<sup>77</sup>, M. Bona<sup>74</sup>, V.G. Bondarenko<sup>95</sup>, M. Bondioli<sup>162</sup>, M. Boonekamp<sup>135</sup>, C.N. Booth<sup>138</sup>, S. Bordini<sup>77</sup>, C. Borer<sup>16</sup>, A. Borisov<sup>127</sup>, G. Borissov<sup>70</sup>, I. Borjanovic<sup>12a</sup>, M. Borri<sup>81</sup>, S. Borroni<sup>86</sup>, V. Bortolotto<sup>133a,133b</sup>, K. Bos<sup>104</sup>, D. Boscherini<sup>19a</sup>, M. Bosman<sup>11</sup>, H. Boterenbrood<sup>104</sup>, D. Botterill<sup>128</sup>, J. Bouchami<sup>92</sup>, J. Boudreau<sup>122</sup>, E.V. Bouhova-Thacker<sup>70</sup>, D. Boumediene<sup>33</sup>, C. Bourdarios<sup>114</sup>, N. Bousson<sup>82</sup>, A. Boveia<sup>30</sup>, J. Boyd<sup>29</sup>, I.R. Boyko<sup>64</sup>, N.I. Bozhko<sup>127</sup>, I. Bozovic-Jelisavcic<sup>12b</sup>, J. Bracinik<sup>17</sup>, A. Braem<sup>29</sup>, P. Branchini<sup>133a</sup>, G.W. Brandenburg<sup>57</sup>, A. Brandt<sup>7</sup>, G. Brandt<sup>117</sup>, O. Brandt<sup>54</sup>, U. Bratzler<sup>155</sup>, B. Brau<sup>83</sup>, J.E. Brau<sup>113</sup>, H.M. Braun<sup>173</sup>, B. Brelrier<sup>157</sup>, J. Bremer<sup>29</sup>, K. Brendlinger<sup>119</sup>, R. Brenner<sup>165</sup>, S. Bressler<sup>170</sup>, D. Britton<sup>53</sup>, F.M. Brochu<sup>27</sup>, I. Brock<sup>20</sup>, R. Brock<sup>87</sup>, T.J. Brodbeck<sup>70</sup>, E. Brodet<sup>152</sup>, F. Broggi<sup>88a</sup>, C. Bromberg<sup>87</sup>, J. Bronner<sup>98</sup>, G. Brooijmans<sup>34</sup>, W.K. Brooks<sup>31b</sup>, G. Brown<sup>81</sup>, H. Brown<sup>7</sup>, P.A. Bruckman de Renstrom<sup>38</sup>, D. Bruncko<sup>143b</sup>, R. Bruneliere<sup>48</sup>, S. Brunet<sup>60</sup>, A. Bruni<sup>19a</sup>, G. Bruni<sup>19a</sup>, M. Bruschi<sup>19a</sup>, T. Buanes<sup>13</sup>, Q. Buat<sup>55</sup>, F. Bucci<sup>49</sup>, J. Buchanan<sup>117</sup>, N.J. Buchanan<sup>2</sup>, P. Buchholz<sup>140</sup>, R.M. Buckingham<sup>117</sup>, A.G. Buckley<sup>45</sup>, S.I. Buda<sup>25a</sup>, I.A. Budagov<sup>64</sup>,



B. Budick<sup>107</sup>, V. Büscher<sup>80</sup>, L. Bugge<sup>116</sup>, O. Bulekov<sup>95</sup>, M. Bunse<sup>42</sup>, T. Buran<sup>116</sup>, H. Burckhart<sup>29</sup>, S. Burdin<sup>72</sup>, T. Burgess<sup>13</sup>, S. Burke<sup>128</sup>, E. Busato<sup>33</sup>, P. Bussey<sup>53</sup>, C.P. Buszello<sup>165</sup>, F. Butin<sup>29</sup>, B. Butler<sup>142</sup>, J.M. Butler<sup>21</sup>, C.M. Buttar<sup>53</sup>, J.M. Butterworth<sup>76</sup>, W. Buttinger<sup>27</sup>, S. Cabrera Urbán<sup>166</sup>, D. Caforio<sup>19a,19b</sup>, O. Cakir<sup>3a</sup>, P. Calafiura<sup>14</sup>, G. Calderini<sup>77</sup>, P. Calfayan<sup>97</sup>, R. Calkins<sup>105</sup>, L.P. Caloba<sup>23a</sup>, R. Caloi<sup>131a,131b</sup>, D. Calvet<sup>33</sup>, S. Calvet<sup>33</sup>, R. Camacho Toro<sup>33</sup>, P. Camarri<sup>132a,132b</sup>, M. Cambiaghi<sup>118a,118b</sup>, D. Cameron<sup>116</sup>, L.M. Caminada<sup>14</sup>, S. Campana<sup>29</sup>, M. Campanelli<sup>76</sup>, V. Canale<sup>101a,101b</sup>, F. Canelli<sup>30,g</sup>, A. Canepa<sup>158a</sup>, J. Cantero<sup>79</sup>, L. Capasso<sup>101a,101b</sup>, M.D.M. Capeans Garrido<sup>29</sup>, I. Caprini<sup>25a</sup>, M. Caprini<sup>25a</sup>, D. Capriotti<sup>98</sup>, M. Capua<sup>36a,36b</sup>, R. Caputo<sup>80</sup>, R. Cardarelli<sup>132a</sup>, T. Carli<sup>29</sup>, G. Carlino<sup>101a</sup>, L. Carminati<sup>88a,88b</sup>, B. Caron<sup>84</sup>, S. Caron<sup>103</sup>, E. Carquin<sup>31b</sup>, G.D. Carrillo Montoya<sup>171</sup>, A.A. Carter<sup>74</sup>, J.R. Carter<sup>27</sup>, J. Carvalho<sup>123a,h</sup>, D. Casadei<sup>107</sup>, M.P. Casado<sup>11</sup>, M. Cascella<sup>121a,121b</sup>, C. Caso<sup>50a,50b,\*</sup>, A.M. Castaneda Hernandez<sup>171</sup>, E. Castaneda-Miranda<sup>171</sup>, V. Castillo Gimenez<sup>166</sup>, N.F. Castro<sup>123a</sup>, G. Cataldi<sup>71a</sup>, A. Catinaccio<sup>29</sup>, J.R. Catmore<sup>29</sup>, A. Cattai<sup>29</sup>, G. Cattani<sup>132a,132b</sup>, S. Caughron<sup>87</sup>, D. Cauz<sup>163a,163c</sup>, P. Cavalleri<sup>77</sup>, D. Cavalli<sup>88a</sup>, M. Cavalli-Sforza<sup>11</sup>, V. Cavasinni<sup>121a,121b</sup>, F. Ceradini<sup>133a,133b</sup>, A.S. Cerqueira<sup>23b</sup>, A. Cerri<sup>29</sup>, L. Cerrito<sup>74</sup>, F. Cerutti<sup>47</sup>, S.A. Cetin<sup>18b</sup>, F. Cevenini<sup>101a,101b</sup>, A. Chafaq<sup>134a</sup>, D. Chakraborty<sup>105</sup>, K. Chan<sup>2</sup>, B. Chapleau<sup>84</sup>, J.D. Chapman<sup>27</sup>, J.W. Chapman<sup>86</sup>, E. Chareyre<sup>77</sup>, D.G. Charlton<sup>17</sup>, V. Chavda<sup>81</sup>, C.A. Chavez Barajas<sup>29</sup>, S. Cheatham<sup>84</sup>, S. Chekanov<sup>5</sup>, S.V. Chekulaev<sup>158a</sup>, G.A. Chelkov<sup>64</sup>, M.A. Chelstowska<sup>103</sup>, C. Chen<sup>63</sup>, H. Chen<sup>24</sup>, S. Chen<sup>32c</sup>, T. Chen<sup>32c</sup>, X. Chen<sup>171</sup>, S. Cheng<sup>32a</sup>, A. Cheplakov<sup>64</sup>, V.F. Chepurinov<sup>64</sup>, R. Cherkaoui El Moursli<sup>134e</sup>, V. Chernyatin<sup>24</sup>, E. Cheu<sup>6</sup>, S.L. Cheung<sup>157</sup>, L. Chevalier<sup>135</sup>, G. Chiefari<sup>101a,101b</sup>, L. Chikovani<sup>51a</sup>, J.T. Childers<sup>29</sup>, A. Chilingarov<sup>70</sup>, G. Chiodini<sup>71a</sup>, A.S. Chisholm<sup>17</sup>, R.T. Chislett<sup>76</sup>, M.V. Chizhov<sup>64</sup>, G. Choudalakis<sup>30</sup>, S. Chouridou<sup>136</sup>, I.A. Christidi<sup>76</sup>, A. Christov<sup>48</sup>, D. Chromek-Burckhart<sup>29</sup>, M.L. Chu<sup>150</sup>, J. Chudoba<sup>124</sup>, G. Ciapetti<sup>131a,131b</sup>, A.K. Ciftci<sup>3a</sup>, R. Ciftci<sup>3a</sup>, D. Cinca<sup>33</sup>, V. Cindro<sup>73</sup>, M.D. Ciobotaru<sup>162</sup>, C. Ciocca<sup>19a</sup>, A. Ciochio<sup>14</sup>, M. Cirilli<sup>86</sup>, M. Citterio<sup>88a</sup>, M. Ciubancan<sup>25a</sup>, A. Clark<sup>49</sup>, P.J. Clark<sup>45</sup>, W. Cleland<sup>122</sup>, J.C. Clemens<sup>82</sup>, B. Clement<sup>55</sup>, C. Clement<sup>145a,145b</sup>, R.W. Clift<sup>128</sup>, Y. Coadou<sup>82</sup>, M. Cobal<sup>163a,163c</sup>, A. Coccaro<sup>171</sup>, J. Cochran<sup>63</sup>, P. Coe<sup>117</sup>, J.G. Cogan<sup>142</sup>, J. Coggeshall<sup>164</sup>, E. Cogneras<sup>176</sup>, J. Colas<sup>4</sup>, A.P. Colijn<sup>104</sup>, N.J. Collins<sup>17</sup>, C. Collins-Tooth<sup>53</sup>, J. Collot<sup>55</sup>, G. Colon<sup>83</sup>, P. Conde Muiño<sup>123a</sup>, E. Coniavitis<sup>117</sup>, M.C. Conidi<sup>11</sup>, M. Consonni<sup>103</sup>, S.M. Consonni<sup>88a,88b</sup>, V. Consorti<sup>48</sup>, S. Constantinescu<sup>25a</sup>, C. Conta<sup>118a,118b</sup>, G. Conti<sup>57</sup>, F. Conventi<sup>101a,i</sup>, J. Cook<sup>29</sup>, M. Cooke<sup>14</sup>, B.D. Cooper<sup>76</sup>, A.M. Cooper-Sarkar<sup>117</sup>, K. Copic<sup>14</sup>, T. Cornelissen<sup>173</sup>, M. Corradi<sup>19a</sup>, F. Corriveau<sup>84,j</sup>, A. Cortes-Gonzalez<sup>164</sup>, G. Cortiana<sup>98</sup>, G. Costa<sup>88a</sup>, M.J. Costa<sup>166</sup>, D. Costanzo<sup>138</sup>, T. Costin<sup>30</sup>, D. Côté<sup>29</sup>, R. Coura Torres<sup>23a</sup>, L. Courneyea<sup>168</sup>, G. Cowan<sup>75</sup>, C. Cowden<sup>27</sup>, B.E. Cox<sup>81</sup>, K. Cranmer<sup>107</sup>, F. Crescioli<sup>121a,121b</sup>, M. Cristinziani<sup>20</sup>, G. Crosetti<sup>36a,36b</sup>, R. Crupi<sup>71a,71b</sup>, S. Crépé-Renaudin<sup>55</sup>, C.-M. Cuciuc<sup>25a</sup>, C. Cuenca Almenar<sup>174</sup>, T. Cuhadar Donszelmann<sup>138</sup>, M. Curatolo<sup>47</sup>, C.J. Curtis<sup>17</sup>, C. Cuthbert<sup>149</sup>, P. Cwetanski<sup>60</sup>, H. Czirr<sup>140</sup>, P. Czodrowski<sup>43</sup>, Z. Czyzula<sup>174</sup>, S. D'Auria<sup>53</sup>, M. D'Onofrio<sup>72</sup>, A. D'Orazio<sup>131a,131b</sup>, P.V.M. Da Silva<sup>23a</sup>, C. Da Via<sup>81</sup>, W. Dabrowski<sup>37</sup>, A. Dafinca<sup>117</sup>, T. Dai<sup>86</sup>, C. Dallapiccola<sup>83</sup>, M. Dam<sup>35</sup>, M. Dameri<sup>50a,50b</sup>, D.S. Damiani<sup>136</sup>, H.O. Danielsson<sup>29</sup>, D. Dannheim<sup>98</sup>, V. Dao<sup>49</sup>, G. Darbo<sup>50a</sup>, G.L. Darlea<sup>25b</sup>, W. Davey<sup>20</sup>, T. Davidek<sup>125</sup>, N. Davidson<sup>85</sup>, R. Davidson<sup>70</sup>, E. Davies<sup>117,c</sup>, M. Davies<sup>92</sup>, A.R. Davison<sup>76</sup>, Y. Davygora<sup>58a</sup>, E. Dawe<sup>141</sup>, I. Dawson<sup>138</sup>, J.W. Dawson<sup>5,\*</sup>, R.K. Daya-Ishmukhametova<sup>22</sup>, K. De<sup>7</sup>, R. de Asmundis<sup>101a</sup>, S. De Castro<sup>19a,19b</sup>, P.E. De Castro Faria Salgado<sup>24</sup>, S. De Cecco<sup>77</sup>, J. de Graat<sup>97</sup>, N. De Groot<sup>103</sup>, P. de Jong<sup>104</sup>, C. De La Taille<sup>114</sup>, H. De la Torre<sup>79</sup>, B. De Lotto<sup>163a,163c</sup>, L. de Mora<sup>70</sup>, L. De Nooij<sup>104</sup>, D. De Pedis<sup>131a</sup>, A. De Salvo<sup>131a</sup>, U. De Sanctis<sup>163a,163c</sup>, A. De Santo<sup>148</sup>, J.B. De Vivie De Regie<sup>114</sup>, G. De Zorzi<sup>131a,131b</sup>, S. Dean<sup>76</sup>, W.J. Dearnaley<sup>70</sup>, R. Debbé<sup>24</sup>, C. Debenedetti<sup>45</sup>, B. Dechenaux<sup>55</sup>, D.V. Dedovich<sup>64</sup>, J. Degenhardt<sup>119</sup>, M. Dehchar<sup>117</sup>, C. Del Papa<sup>163a,163c</sup>, J. Del Peso<sup>79</sup>, T. Del Prete<sup>121a,121b</sup>, T. Delemontex<sup>55</sup>, M. Deliyergiyev<sup>73</sup>, A. Dell'Acqua<sup>29</sup>, L. Dell'Asta<sup>21</sup>, M. Della Pietra<sup>101a,i</sup>, D. della Volpe<sup>101a,101b</sup>, M. Delmastro<sup>4</sup>, N. Delruelle<sup>29</sup>, P.A. Delsart<sup>55</sup>, C. Deluca<sup>147</sup>, S. Demers<sup>174</sup>, M. Demichev<sup>64</sup>, B. Demirköz<sup>11,k</sup>, J. Deng<sup>162</sup>, S.P. Denisov<sup>127</sup>, D. Derendarz<sup>38</sup>, J.E. Derkaoui<sup>134d</sup>, F. Derue<sup>77</sup>, P. Dervan<sup>72</sup>, K. Desch<sup>20</sup>, E. Devetak<sup>147</sup>, P.O. Deviveiros<sup>104</sup>, A. Dewhurst<sup>128</sup>, B. DeWilde<sup>147</sup>, S. Dhaliwal<sup>157</sup>, R. Dhullipudi<sup>24,l</sup>, A. Di Ciaccio<sup>132a,132b</sup>, L. Di Ciaccio<sup>4</sup>, A. Di Girolamo<sup>29</sup>, B. Di Girolamo<sup>29</sup>, S. Di Luise<sup>133a,133b</sup>, A. Di Mattia<sup>171</sup>, B. Di Micco<sup>29</sup>, R. Di Nardo<sup>47</sup>, A. Di Simone<sup>132a,132b</sup>, R. Di Sipio<sup>19a,19b</sup>, M.A. Diaz<sup>31a</sup>, F. Diblen<sup>18c</sup>, E.B. Diehl<sup>86</sup>, J. Dietrich<sup>41</sup>, T.A. Dietzsch<sup>58a</sup>, S. Diglio<sup>85</sup>, K. Dindar Yagci<sup>39</sup>, J. Dingfelder<sup>20</sup>, C. Dionisi<sup>131a,131b</sup>, P. Dita<sup>25a</sup>, S. Dita<sup>25a</sup>,

F. Dittus<sup>29</sup>, F. Djama<sup>82</sup>, T. Djobava<sup>51b</sup>, M.A.B. do Vale<sup>23c</sup>, A. Do Valle Wemans<sup>123a</sup>, T.K.O. Doan<sup>4</sup>, M. Dobbs<sup>84</sup>, R. Dobinson<sup>29,\*</sup>, D. Dobos<sup>29</sup>, E. Dobson<sup>29,m</sup>, J. Dodd<sup>34</sup>, C. Doglioni<sup>49</sup>, T. Doherty<sup>53</sup>, Y. Doi<sup>65,\*</sup>, J. Dolejsi<sup>125</sup>, I. Dolenc<sup>73</sup>, Z. Dolezal<sup>125</sup>, B.A. Dolgoshein<sup>95,\*</sup>, T. Dohmae<sup>154</sup>, M. Donadelli<sup>23d</sup>, M. Donega<sup>119</sup>, J. Donini<sup>33</sup>, J. Dopke<sup>29</sup>, A. Doria<sup>101a</sup>, A. Dos Anjos<sup>171</sup>, M. Dosil<sup>11</sup>, A. Dotti<sup>121a,121b</sup>, M.T. Dova<sup>69</sup>, A.D. Doxiadis<sup>104</sup>, A.T. Doyle<sup>53</sup>, Z. Drasal<sup>125</sup>, J. Drees<sup>173</sup>, N. Dressnandt<sup>119</sup>, H. Drevermann<sup>29</sup>, C. Driouichi<sup>35</sup>, M. Dris<sup>9</sup>, J. Dubbert<sup>98</sup>, S. Dube<sup>14</sup>, E. Duchovni<sup>170</sup>, G. Duckeck<sup>97</sup>, A. Dudarev<sup>29</sup>, F. Dudziak<sup>63</sup>, M. Dührssen<sup>29</sup>, I.P. Duerdoth<sup>81</sup>, L. Dufлот<sup>114</sup>, M-A. Dufour<sup>84</sup>, M. Dunford<sup>29</sup>, H. Duran Yildiz<sup>3a</sup>, R. Duxfield<sup>138</sup>, M. Dwuznik<sup>37</sup>, F. Dydak<sup>29</sup>, M. Düren<sup>52</sup>, W.L. Ebenstein<sup>44</sup>, J. Ebke<sup>97</sup>, S. Eckweiler<sup>80</sup>, K. Edmonds<sup>80</sup>, C.A. Edwards<sup>75</sup>, N.C. Edwards<sup>53</sup>, W. Ehrenfeld<sup>41</sup>, T. Ehrich<sup>98</sup>, T. Eifert<sup>142</sup>, G. Eigen<sup>13</sup>, K. Einsweiler<sup>14</sup>, E. Eisenhandler<sup>74</sup>, T. Ekelof<sup>165</sup>, M. El Kacimi<sup>134c</sup>, M. Ellert<sup>165</sup>, S. Elles<sup>4</sup>, F. Ellinghaus<sup>80</sup>, K. Ellis<sup>74</sup>, N. Ellis<sup>29</sup>, J. Elmsheuser<sup>97</sup>, M. Elsing<sup>29</sup>, D. Emeliyanov<sup>128</sup>, R. Engelmann<sup>147</sup>, A. Engl<sup>97</sup>, B. Epp<sup>61</sup>, A. Eppig<sup>86</sup>, J. Erdmann<sup>54</sup>, A. Ereditato<sup>16</sup>, D. Eriksson<sup>145a</sup>, J. Ernst<sup>1</sup>, M. Ernst<sup>24</sup>, J. Ernwein<sup>135</sup>, D. Errede<sup>164</sup>, S. Errede<sup>164</sup>, E. Ertel<sup>80</sup>, M. Escalier<sup>114</sup>, C. Escobar<sup>122</sup>, X. Espinal Curull<sup>11</sup>, B. Esposito<sup>47</sup>, F. Etienne<sup>82</sup>, A.I. Etienvre<sup>135</sup>, E. Etzion<sup>152</sup>, D. Evangelakou<sup>54</sup>, H. Evans<sup>60</sup>, L. Fabbri<sup>19a,19b</sup>, C. Fabre<sup>29</sup>, R.M. Fakhrutdinov<sup>127</sup>, S. Falciano<sup>131a</sup>, Y. Fang<sup>171</sup>, M. Fanti<sup>88a,88b</sup>, A. Farbin<sup>7</sup>, A. Farilla<sup>133a</sup>, J. Farley<sup>147</sup>, T. Farooque<sup>157</sup>, S. Farrell<sup>162</sup>, S.M. Farrington<sup>117</sup>, P. Farthouat<sup>29</sup>, P. Fassnacht<sup>29</sup>, D. Fassouliotis<sup>8</sup>, B. Fatholahzadeh<sup>157</sup>, A. Favareto<sup>88a,88b</sup>, L. Fayard<sup>114</sup>, S. Fazio<sup>36a,36b</sup>, R. Febbraro<sup>33</sup>, P. Federic<sup>143a</sup>, O.L. Fedin<sup>120</sup>, W. Fedorko<sup>87</sup>, M. Fehling-Kaschek<sup>48</sup>, L. Feligioni<sup>82</sup>, D. Fellmann<sup>5</sup>, C. Feng<sup>32d</sup>, E.J. Feng<sup>30</sup>, A.B. Fenyuk<sup>127</sup>, J. Ferencei<sup>143b</sup>, J. Ferland<sup>92</sup>, W. Fernando<sup>108</sup>, S. Ferrag<sup>53</sup>, J. Ferrando<sup>53</sup>, V. Ferrara<sup>41</sup>, A. Ferrari<sup>165</sup>, P. Ferrari<sup>104</sup>, R. Ferrari<sup>118a</sup>, D.E. Ferreira de Lima<sup>53</sup>, A. Ferrer<sup>166</sup>, M.L. Ferrer<sup>47</sup>, D. Ferrere<sup>49</sup>, C. Ferretti<sup>86</sup>, A. Ferretto Parodi<sup>50a,50b</sup>, M. Fiascaris<sup>30</sup>, F. Fiedler<sup>80</sup>, A. Filipčič<sup>73</sup>, A. Filippas<sup>9</sup>, F. Filthaut<sup>103</sup>, M. Fincke-Keeler<sup>168</sup>, M.C.N. Fiolhais<sup>123a,h</sup>, L. Fiorini<sup>166</sup>, A. Firan<sup>39</sup>, G. Fischer<sup>41</sup>, P. Fischer<sup>20</sup>, M.J. Fisher<sup>108</sup>, M. Flechl<sup>48</sup>, I. Fleck<sup>140</sup>, J. Fleckner<sup>80</sup>, P. Fleischmann<sup>172</sup>, S. Fleischmann<sup>173</sup>, T. Flick<sup>173</sup>, A. Floderus<sup>78</sup>, L.R. Flores Castillo<sup>171</sup>, M.J. Flowerdew<sup>98</sup>, M. Fokitis<sup>9</sup>, T. Fonseca Martin<sup>16</sup>, D.A. Forbush<sup>137</sup>, A. Formica<sup>135</sup>, A. Forti<sup>81</sup>, D. Fortin<sup>158a</sup>, J.M. Foster<sup>81</sup>, D. Fournier<sup>114</sup>, A. Foussat<sup>29</sup>, A.J. Fowler<sup>44</sup>, K. Fowler<sup>136</sup>, H. Fox<sup>70</sup>, P. Francavilla<sup>11</sup>, S. Franchino<sup>118a,118b</sup>, D. Francis<sup>29</sup>, T. Frank<sup>170</sup>, M. Franklin<sup>57</sup>, S. Franz<sup>29</sup>, M. Fraternali<sup>118a,118b</sup>, S. Fratina<sup>119</sup>, S.T. French<sup>27</sup>, F. Friedrich<sup>43</sup>, R. Froeschl<sup>29</sup>, D. Froidevaux<sup>29</sup>, J.A. Frost<sup>27</sup>, C. Fukunaga<sup>155</sup>, E. Fullana Torregrosa<sup>29</sup>, J. Fuster<sup>166</sup>, C. Gabaldon<sup>29</sup>, O. Gabizon<sup>170</sup>, T. Gadfort<sup>24</sup>, S. Gadomski<sup>49</sup>, G. Gagliardi<sup>50a,50b</sup>, P. Gagnon<sup>60</sup>, C. Galea<sup>97</sup>, E.J. Gallas<sup>117</sup>, V. Gallo<sup>16</sup>, B.J. Gallop<sup>128</sup>, P. Gallus<sup>124</sup>, K.K. Gan<sup>108</sup>, Y.S. Gao<sup>142,e</sup>, V.A. Gapienko<sup>127</sup>, A. Gaponenko<sup>14</sup>, F. Garbersen<sup>174</sup>, M. Garcia-Sciveres<sup>14</sup>, C. García<sup>166</sup>, J.E. García Navarro<sup>166</sup>, R.W. Gardner<sup>30</sup>, N. Garelli<sup>29</sup>, H. Garitaonandia<sup>104</sup>, V. Garonne<sup>29</sup>, J. Garvey<sup>17</sup>, C. Gatti<sup>47</sup>, G. Gaudio<sup>118a</sup>, B. Gaur<sup>140</sup>, L. Gauthier<sup>135</sup>, P. Gauzzi<sup>131a,131b</sup>, I.L. Gavrilenko<sup>93</sup>, C. Gay<sup>167</sup>, G. Gaycken<sup>20</sup>, J-C. Gayde<sup>29</sup>, E.N. Gazis<sup>9</sup>, P. Ge<sup>32d</sup>, C.N.P. Gee<sup>128</sup>, D.A.A. Geerts<sup>104</sup>, Ch. Geich-Gimbel<sup>20</sup>, K. Gellerstedt<sup>145a,145b</sup>, C. Gemme<sup>50a</sup>, A. Gemmell<sup>53</sup>, M.H. Genest<sup>55</sup>, S. Gentile<sup>131a,131b</sup>, M. George<sup>54</sup>, S. George<sup>75</sup>, P. Gerlach<sup>173</sup>, A. Gershon<sup>152</sup>, C. Geweniger<sup>58a</sup>, H. Ghazlane<sup>134b</sup>, N. Ghodbane<sup>33</sup>, B. Giacobbe<sup>19a</sup>, S. Giagu<sup>131a,131b</sup>, V. Giakoumopoulou<sup>8</sup>, V. Giangiobbe<sup>11</sup>, F. Gianotti<sup>29</sup>, B. Gibbard<sup>24</sup>, A. Gibson<sup>157</sup>, S.M. Gibson<sup>29</sup>, L.M. Gilbert<sup>117</sup>, V. Gilevsky<sup>90</sup>, D. Gillberg<sup>28</sup>, A.R. Gillman<sup>128</sup>, D.M. Gingrich<sup>2,d</sup>, J. Ginzburg<sup>152</sup>, N. Giokaris<sup>8</sup>, M.P. Giordani<sup>163c</sup>, R. Giordano<sup>101a,101b</sup>, F.M. Giorgi<sup>15</sup>, P. Giovannini<sup>98</sup>, P.F. Giraud<sup>135</sup>, D. Giugni<sup>88a</sup>, M. Giunta<sup>92</sup>, P. Giusti<sup>19a</sup>, B.K. Gjelsten<sup>116</sup>, L.K. Gladilin<sup>96</sup>, C. Glasman<sup>79</sup>, J. Glatzer<sup>48</sup>, A. Glazov<sup>41</sup>, K.W. Glitza<sup>173</sup>, G.L. Glonti<sup>64</sup>, J.R. Goddard<sup>74</sup>, J. Godfrey<sup>141</sup>, J. Godlewski<sup>29</sup>, M. Goebel<sup>41</sup>, T. Göpfert<sup>43</sup>, C. Goeringer<sup>80</sup>, C. Gössling<sup>42</sup>, T. Göttfert<sup>98</sup>, S. Goldfarb<sup>86</sup>, T. Golling<sup>174</sup>, A. Gomes<sup>123a,b</sup>, L.S. Gomez Fajardo<sup>41</sup>, R. Gonçalves<sup>75</sup>, J. Goncalves Pinto Firmino Da Costa<sup>41</sup>, L. Gonella<sup>20</sup>, A. Gonidec<sup>29</sup>, S. Gonzalez<sup>171</sup>, S. González de la Hoz<sup>166</sup>, G. Gonzalez Parra<sup>11</sup>, M.L. Gonzalez Silva<sup>26</sup>, S. Gonzalez-Sevilla<sup>49</sup>, J.J. Goodson<sup>147</sup>, L. Goossens<sup>29</sup>, P.A. Gorbounov<sup>94</sup>, H.A. Gordon<sup>24</sup>, I. Gorelov<sup>102</sup>, G. Gorfine<sup>173</sup>, B. Gorini<sup>29</sup>, E. Gorini<sup>71a,71b</sup>, A. Gorišek<sup>73</sup>, E. Gornicki<sup>38</sup>, V.N. Goryachev<sup>127</sup>, B. Gosdzik<sup>41</sup>, A.T. Goshaw<sup>5</sup>, M. Gosselink<sup>104</sup>, M.I. Gostkin<sup>64</sup>, I. Gough Eschrich<sup>162</sup>, M. Goughri<sup>134a</sup>, D. Goujdami<sup>134c</sup>, M.P. Goulette<sup>49</sup>, A.G. Goussiou<sup>137</sup>, C. Goy<sup>4</sup>, S. Gozpinar<sup>22</sup>, I. Grabowska-Bold<sup>37</sup>, P. Grafström<sup>29</sup>, K-J. Grahn<sup>41</sup>, F. Grancagnolo<sup>71a</sup>, S. Grancagnolo<sup>15</sup>, V. Grassi<sup>147</sup>, V. Gratchev<sup>120</sup>, N. Grau<sup>34</sup>, H.M. Gray<sup>29</sup>, J.A. Gray<sup>147</sup>, E. Graziani<sup>133a</sup>, O.G. Grebenyuk<sup>120</sup>, T. Greenshaw<sup>72</sup>, Z.D. Greenwood<sup>24,i</sup>, K. Gregersen<sup>35</sup>, I.M. Gregor<sup>41</sup>, P. Grenier<sup>142</sup>, J. Griffiths<sup>137</sup>, N. Grigalashvili<sup>64</sup>, A.A. Grillo<sup>136</sup>, S. Grinstein<sup>11</sup>,



Y.V. Grishkevich<sup>96</sup>, J.-F. Grivaz<sup>114</sup>, M. Groh<sup>98</sup>, E. Gross<sup>170</sup>, J. Grosse-Knetter<sup>54</sup>, J. Groth-Jensen<sup>170</sup>, K. Grybel<sup>140</sup>, V.J. Guarino<sup>5</sup>, D. Guest<sup>174</sup>, C. Guicheney<sup>33</sup>, A. Guida<sup>71a,71b</sup>, S. Guindon<sup>54</sup>, H. Guler<sup>84,n</sup>, J. Gunther<sup>124</sup>, B. Guo<sup>157</sup>, J. Guo<sup>34</sup>, A. Gupta<sup>30</sup>, Y. Gusakov<sup>64</sup>, V.N. Gushchin<sup>127</sup>, P. Gutierrez<sup>110</sup>, N. Guttman<sup>152</sup>, O. Gutzwiller<sup>171</sup>, C. Guyot<sup>135</sup>, C. Gwenlan<sup>117</sup>, C.B. Gwilliam<sup>72</sup>, A. Haas<sup>142</sup>, S. Haas<sup>29</sup>, C. Haber<sup>14</sup>, H.K. Hadavand<sup>39</sup>, D.R. Hadley<sup>17</sup>, P. Haefner<sup>98</sup>, F. Hahn<sup>29</sup>, S. Haider<sup>29</sup>, Z. Hajduk<sup>38</sup>, H. Hakobyan<sup>175</sup>, D. Hall<sup>117</sup>, J. Haller<sup>54</sup>, K. Hamacher<sup>173</sup>, P. Hamal<sup>112</sup>, M. Hamer<sup>54</sup>, A. Hamilton<sup>144b,o</sup>, S. Hamilton<sup>160</sup>, H. Han<sup>32a</sup>, L. Han<sup>32b</sup>, K. Hanagaki<sup>115</sup>, K. Hanawa<sup>159</sup>, M. Hance<sup>14</sup>, C. Handel<sup>80</sup>, P. Hanke<sup>58a</sup>, J.R. Hansen<sup>35</sup>, J.B. Hansen<sup>35</sup>, J.D. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P. Hansson<sup>142</sup>, K. Hara<sup>159</sup>, G.A. Hare<sup>136</sup>, T. Harenberg<sup>173</sup>, S. Harkusha<sup>89</sup>, D. Harper<sup>86</sup>, R.D. Harrington<sup>45</sup>, O.M. Harris<sup>137</sup>, K. Harrison<sup>17</sup>, J. Hartert<sup>48</sup>, F. Hartjes<sup>104</sup>, T. Haruyama<sup>65</sup>, A. Harvey<sup>56</sup>, S. Hasegawa<sup>100</sup>, Y. Hasegawa<sup>139</sup>, S. Hassani<sup>135</sup>, M. Hatch<sup>29</sup>, D. Hauff<sup>98</sup>, S. Haug<sup>16</sup>, M. Hauschild<sup>29</sup>, R. Hauser<sup>87</sup>, M. Havranek<sup>20</sup>, B.M. Hawes<sup>117</sup>, C.M. Hawkes<sup>17</sup>, R.J. Hawkins<sup>29</sup>, A.D. Hawkins<sup>78</sup>, D. Hawkins<sup>162</sup>, T. Hayakawa<sup>66</sup>, T. Hayashi<sup>159</sup>, D. Hayden<sup>75</sup>, H.S. Hayward<sup>72</sup>, S.J. Haywood<sup>128</sup>, E. Hazen<sup>21</sup>, M. He<sup>32d</sup>, S.J. Head<sup>17</sup>, V. Hedberg<sup>78</sup>, L. Heelan<sup>7</sup>, S. Heim<sup>87</sup>, B. Heinemann<sup>14</sup>, S. Heisterkamp<sup>35</sup>, L. Helary<sup>4</sup>, C. Heller<sup>97</sup>, M. Heller<sup>29</sup>, S. Hellman<sup>145a,145b</sup>, D. Hellmich<sup>20</sup>, C. Helsens<sup>11</sup>, R.C.W. Henderson<sup>70</sup>, M. Henke<sup>58a</sup>, A. Henrichs<sup>54</sup>, A.M. Henriques Correia<sup>29</sup>, S. Henrot-Versille<sup>114</sup>, F. Henry-Couannier<sup>82</sup>, C. Hensel<sup>54</sup>, T. Henß<sup>173</sup>, C.M. Hernandez<sup>7</sup>, Y. Hernández Jiménez<sup>166</sup>, R. Herrberg<sup>15</sup>, A.D. Hershenhorn<sup>151</sup>, G. Herten<sup>48</sup>, R. Hertenberger<sup>97</sup>, L. Hervas<sup>29</sup>, G.G. Hesketh<sup>76</sup>, N.P. Hessey<sup>104</sup>, E. Higón-Rodríguez<sup>166</sup>, D. Hill<sup>5,\*</sup>, J.C. Hill<sup>27</sup>, N. Hill<sup>5</sup>, K.H. Hiller<sup>41</sup>, S. Hillert<sup>20</sup>, S.J. Hillier<sup>17</sup>, I. Hinchliffe<sup>14</sup>, E. Hines<sup>119</sup>, M. Hirose<sup>115</sup>, F. Hirsch<sup>42</sup>, D. Hirschbuehl<sup>173</sup>, J. Hobbs<sup>147</sup>, N. Hod<sup>152</sup>, M.C. Hodgkinson<sup>138</sup>, P. Hodgson<sup>138</sup>, A. Hoecker<sup>29</sup>, M.R. Hoefkamp<sup>102</sup>, J. Hoffman<sup>39</sup>, D. Hoffmann<sup>82</sup>, M. Hohlfeld<sup>80</sup>, M. Holder<sup>140</sup>, S.O. Holmgren<sup>145a</sup>, T. Holy<sup>126</sup>, J.L. Holzbauer<sup>87</sup>, Y. Homma<sup>66</sup>, T.M. Hong<sup>119</sup>, L. Hooft van Huysduynen<sup>107</sup>, T. Horazdovsky<sup>126</sup>, C. Horn<sup>142</sup>, S. Horner<sup>48</sup>, J.-Y. Hostachy<sup>55</sup>, S. Hou<sup>150</sup>, M.A. Houlden<sup>72</sup>, A. Hoummada<sup>134a</sup>, J. Howarth<sup>81</sup>, D.F. Howell<sup>117</sup>, I. Hristova<sup>15</sup>, J. Hrivnac<sup>114</sup>, I. Hruska<sup>124</sup>, T. Hryn'ova<sup>4</sup>, P.J. Hsu<sup>80</sup>, S.-C. Hsu<sup>14</sup>, G.S. Huang<sup>110</sup>, Z. Hubacek<sup>126</sup>, F. Hubaut<sup>82</sup>, F. Huegging<sup>20</sup>, A. Huettmann<sup>41</sup>, T.B. Huffman<sup>117</sup>, E.W. Hughes<sup>34</sup>, G. Hughes<sup>70</sup>, R.E. Hughes-Jones<sup>81</sup>, M. Huhtinen<sup>29</sup>, P. Hurst<sup>57</sup>, M. Hurwitz<sup>14</sup>, U. Husemann<sup>41</sup>, N. Huseynov<sup>64,p</sup>, J. Huston<sup>87</sup>, J. Huth<sup>57</sup>, G. Iacobucci<sup>49</sup>, G. Iakovidis<sup>9</sup>, M. Ibbotson<sup>81</sup>, I. Ibragimov<sup>140</sup>, R. Ichimiya<sup>66</sup>, L. Iconomidou-Fayard<sup>114</sup>, J. Idarraga<sup>114</sup>, P. Iengo<sup>101a</sup>, O. Igonkina<sup>104</sup>, Y. Ikegami<sup>65</sup>, M. Ikeno<sup>65</sup>, Y. Ilchenko<sup>39</sup>, D. Iliadis<sup>153</sup>, N. Ilic<sup>157</sup>, M. Imori<sup>154</sup>, T. Ince<sup>20</sup>, J. Inigo-Golfín<sup>29</sup>, P. Ioannou<sup>8</sup>, M. Iodice<sup>133a</sup>, V. Ippolito<sup>131a,131b</sup>, A. Irls Quiles<sup>166</sup>, C. Isaksson<sup>165</sup>, A. Ishikawa<sup>66</sup>, M. Ishino<sup>67</sup>, R. Ishmukhametov<sup>39</sup>, C. Issever<sup>117</sup>, S. Istin<sup>18a</sup>, A.V. Ivashin<sup>127</sup>, W. Iwanski<sup>38</sup>, H. Iwasaki<sup>65</sup>, J.M. Izen<sup>40</sup>, V. Izzo<sup>101a</sup>, B. Jackson<sup>119</sup>, J.N. Jackson<sup>72</sup>, P. Jackson<sup>142</sup>, M.R. Jaekel<sup>29</sup>, V. Jain<sup>60</sup>, K. Jakobs<sup>48</sup>, S. Jakobsen<sup>35</sup>, J. Jakubek<sup>126</sup>, D.K. Jana<sup>110</sup>, E. Jansen<sup>76</sup>, H. Jansen<sup>29</sup>, A. Jantsch<sup>98</sup>, M. Janus<sup>48</sup>, G. Jarlskog<sup>78</sup>, L. Jeanty<sup>57</sup>, K. Jelen<sup>37</sup>, I. Jen-La Plante<sup>30</sup>, P. Jenni<sup>29</sup>, A. Jeremie<sup>4</sup>, P. Jež<sup>35</sup>, S. Jézéquel<sup>4</sup>, M.K. Jha<sup>19a</sup>, H. Ji<sup>171</sup>, W. Ji<sup>80</sup>, J. Jia<sup>147</sup>, Y. Jiang<sup>32b</sup>, M. Jimenez Belenguer<sup>41</sup>, G. Jin<sup>32b</sup>, S. Jin<sup>32a</sup>, O. Jinnouchi<sup>156</sup>, M.D. Joergensen<sup>35</sup>, D. Joffe<sup>39</sup>, L.G. Johansen<sup>13</sup>, M. Johansen<sup>145a,145b</sup>, K.E. Johansson<sup>145a</sup>, P. Johansson<sup>138</sup>, S. Johnert<sup>41</sup>, K.A. Johns<sup>6</sup>, K. Jon-And<sup>145a,145b</sup>, G. Jones<sup>117</sup>, R.W.L. Jones<sup>70</sup>, T.W. Jones<sup>76</sup>, T.J. Jones<sup>72</sup>, O. Jonsson<sup>29</sup>, C. Joram<sup>29</sup>, P.M. Jorge<sup>123a</sup>, J. Joseph<sup>14</sup>, K.D. Joshi<sup>81</sup>, J. Jovicevic<sup>146</sup>, T. Jovin<sup>12b</sup>, X. Ju<sup>171</sup>, C.A. Jung<sup>42</sup>, R.M. Jungst<sup>29</sup>, V. Juranek<sup>124</sup>, P. Jussel<sup>61</sup>, A. Juste Rozas<sup>11</sup>, V.V. Kabachenko<sup>127</sup>, S. Kabana<sup>16</sup>, M. Kaci<sup>166</sup>, A. Kaczmarska<sup>38</sup>, P. Kadlecik<sup>35</sup>, M. Kado<sup>114</sup>, H. Kagan<sup>108</sup>, M. Kagan<sup>57</sup>, S. Kaiser<sup>98</sup>, E. Kajomovitz<sup>151</sup>, S. Kalinin<sup>173</sup>, L.V. Kalinovskaya<sup>64</sup>, S. Kama<sup>39</sup>, N. Kanaya<sup>154</sup>, M. Kaneda<sup>29</sup>, S. Kaneti<sup>27</sup>, T. Kanno<sup>156</sup>, V.A. Kantserov<sup>95</sup>, J. Kanzaki<sup>65</sup>, B. Kaplan<sup>174</sup>, A. Kapliy<sup>30</sup>, J. Kaplon<sup>29</sup>, D. Kar<sup>43</sup>, M. Karagounis<sup>20</sup>, M. Karagoz<sup>117</sup>, M. Karnevskiy<sup>41</sup>, V. Kartvelishvili<sup>70</sup>, A.N. Karyukhin<sup>127</sup>, L. Kashif<sup>171</sup>, G. Kasieczka<sup>58b</sup>, R.D. Kass<sup>108</sup>, A. Kastanas<sup>13</sup>, M. Kataoka<sup>4</sup>, Y. Kataoka<sup>154</sup>, E. Katsoufis<sup>9</sup>, J. Katzy<sup>41</sup>, V. Kaushik<sup>6</sup>, K. Kawagoe<sup>66</sup>, T. Kawamoto<sup>154</sup>, G. Kawamura<sup>80</sup>, M.S. Kayl<sup>104</sup>, V.A. Kazanin<sup>106</sup>, M.Y. Kazarinov<sup>64</sup>, R. Keeler<sup>168</sup>, R. Kehoe<sup>39</sup>, M. Keil<sup>54</sup>, G.D. Kekelidze<sup>64</sup>, J.S. Keller<sup>137</sup>, J. Kennedy<sup>97</sup>, M. Kenyon<sup>53</sup>, O. Kepka<sup>124</sup>, N. Kerschen<sup>29</sup>, B.P. Kerševan<sup>73</sup>, S. Kersten<sup>173</sup>, K. Kessoku<sup>154</sup>, J. Keung<sup>157</sup>, F. Khalil-zada<sup>10</sup>, H. Khandanyan<sup>164</sup>, A. Khanov<sup>111</sup>, D. Kharchenko<sup>64</sup>, A. Khodinov<sup>95</sup>, A.G. Kholodenko<sup>127</sup>, A. Khomich<sup>58a</sup>, T.J. Khoo<sup>27</sup>, G. Khoriauli<sup>20</sup>, A. Khoroshilov<sup>173</sup>, N. Khovanskiy<sup>64</sup>, V. Khovanskiy<sup>94</sup>, E. Khramov<sup>64</sup>, J. Khubua<sup>51b</sup>, H. Kim<sup>145a,145b</sup>, M.S. Kim<sup>2</sup>, S.H. Kim<sup>159</sup>, N. Kimura<sup>169</sup>, O. Kind<sup>15</sup>, B.T. King<sup>72</sup>, M. King<sup>66</sup>, R.S.B. King<sup>117</sup>, J. Kirk<sup>128</sup>, L.E. Kirsch<sup>22</sup>, A.E. Kiryunin<sup>98</sup>, T. Kishimoto<sup>66</sup>, D. Kisielewska<sup>37</sup>,

T. Kittelmann<sup>122</sup>, A.M. Kiver<sup>127</sup>, E. Kladiva<sup>143b</sup>, M. Klein<sup>72</sup>, U. Klein<sup>72</sup>, K. Kleinknecht<sup>80</sup>, M. Klemetti<sup>84</sup>, A. Klier<sup>170</sup>, P. Klimek<sup>145a,145b</sup>, A. Klimentov<sup>24</sup>, R. Klingenberg<sup>42</sup>, J.A. Klinger<sup>81</sup>, E.B. Klinkby<sup>35</sup>, T. Klioutchnikova<sup>29</sup>, P.F. Klok<sup>103</sup>, S. Klous<sup>104</sup>, E.-E. Kluge<sup>58a</sup>, T. Kluge<sup>72</sup>, P. Kluit<sup>104</sup>, S. Kluth<sup>98</sup>, N.S. Knecht<sup>157</sup>, E. Kneringer<sup>61</sup>, J. Knobloch<sup>29</sup>, E.B.F.G. Knoops<sup>82</sup>, A. Knue<sup>54</sup>, B.R. Ko<sup>44</sup>, T. Kobayashi<sup>154</sup>, M. Kobel<sup>43</sup>, M. Kocian<sup>142</sup>, P. Kodys<sup>125</sup>, K. Köneke<sup>29</sup>, A.C. König<sup>103</sup>, S. Koenig<sup>80</sup>, L. Köpke<sup>80</sup>, F. Koetsveld<sup>103</sup>, P. Koevesarki<sup>20</sup>, T. Koffas<sup>28</sup>, E. Koffeman<sup>104</sup>, L.A. Kogan<sup>117</sup>, F. Kohn<sup>54</sup>, Z. Kohout<sup>126</sup>, T. Kohriki<sup>65</sup>, T. Koi<sup>142</sup>, T. Kokott<sup>20</sup>, G.M. Kolachev<sup>106</sup>, H. Kolanoski<sup>15</sup>, V. Kolesnikov<sup>64</sup>, I. Koletsou<sup>88a</sup>, J. Koll<sup>87</sup>, M. Kollfrath<sup>48</sup>, S.D. Kolya<sup>81</sup>, A.A. Komar<sup>93</sup>, Y. Komori<sup>154</sup>, T. Kondo<sup>65</sup>, T. Kono<sup>41,q</sup>, A.I. Kononov<sup>48</sup>, R. Konoplich<sup>107,r</sup>, N. Konstantinidis<sup>76</sup>, A. Kootz<sup>173</sup>, S. Koperny<sup>37</sup>, K. Korcyl<sup>38</sup>, K. Kordas<sup>153</sup>, V. Koreshev<sup>127</sup>, A. Korn<sup>117</sup>, A. Korol<sup>106</sup>, I. Korolkov<sup>11</sup>, E.V. Korolkova<sup>138</sup>, V.A. Korotkov<sup>127</sup>, O. Kortner<sup>98</sup>, S. Kortner<sup>98</sup>, V.V. Kostyukhin<sup>20</sup>, M.J. Kotamäki<sup>29</sup>, S. Kotov<sup>98</sup>, V.M. Kotov<sup>64</sup>, A. Kotwal<sup>44</sup>, C. Kourkoumelis<sup>8</sup>, V. Kouskoura<sup>153</sup>, A. Koutsman<sup>158a</sup>, R. Kowalewski<sup>168</sup>, T.Z. Kowalski<sup>37</sup>, W. Kozanecki<sup>135</sup>, A.S. Kozhin<sup>127</sup>, V. Kral<sup>126</sup>, V.A. Kramarenko<sup>96</sup>, G. Kramberger<sup>73</sup>, M.W. Krasny<sup>77</sup>, A. Krasznahorkay<sup>107</sup>, J. Kraus<sup>87</sup>, J.K. Kraus<sup>20</sup>, A. Kreisel<sup>152</sup>, F. Krejci<sup>126</sup>, J. Kretzschmar<sup>72</sup>, N. Krieger<sup>54</sup>, P. Krieger<sup>157</sup>, K. Kroeninger<sup>54</sup>, H. Kroha<sup>98</sup>, J. Kroll<sup>119</sup>, J. Kroseberg<sup>20</sup>, J. Krstic<sup>12a</sup>, U. Kruchonak<sup>64</sup>, H. Krüger<sup>20</sup>, T. Kruker<sup>16</sup>, N. Krumnack<sup>63</sup>, Z.V. Krumshteyn<sup>64</sup>, A. Kruth<sup>20</sup>, T. Kubota<sup>85</sup>, S. Kuday<sup>3a</sup>, S. Kuehn<sup>48</sup>, A. Kugel<sup>58c</sup>, T. Kuhl<sup>41</sup>, D. Kuhn<sup>61</sup>, V. Kukhtin<sup>64</sup>, Y. Kulchitsky<sup>89</sup>, S. Kuleshov<sup>31b</sup>, C. Kummer<sup>97</sup>, M. Kuna<sup>77</sup>, N. Kundu<sup>117</sup>, J. Kunkle<sup>119</sup>, A. Kupco<sup>124</sup>, H. Kurashige<sup>66</sup>, M. Kurata<sup>159</sup>, Y.A. Kurochkin<sup>89</sup>, V. Kus<sup>124</sup>, E.S. Kuwertz<sup>146</sup>, M. Kuze<sup>156</sup>, J. Kvita<sup>141</sup>, R. Kwee<sup>15</sup>, A. La Rosa<sup>49</sup>, L. La Rotonda<sup>36a,36b</sup>, L. Labarga<sup>79</sup>, J. Labbe<sup>4</sup>, S. Lablak<sup>134a</sup>, C. Lacasta<sup>166</sup>, F. Lacava<sup>131a,131b</sup>, H. Lacker<sup>15</sup>, D. Lacour<sup>77</sup>, V.R. Lacuesta<sup>166</sup>, E. Ladygin<sup>64</sup>, R. Lafaye<sup>4</sup>, B. Laforge<sup>77</sup>, T. Lagouri<sup>79</sup>, S. Lai<sup>48</sup>, E. Laisne<sup>55</sup>, M. Lamanna<sup>29</sup>, L. Lambourne<sup>76</sup>, C.L. Lampen<sup>6</sup>, W. Lampl<sup>6</sup>, E. Lancon<sup>135</sup>, U. Landgraf<sup>48</sup>, M.P.J. Landon<sup>74</sup>, J.L. Lane<sup>81</sup>, C. Lange<sup>41</sup>, A.J. Lankford<sup>162</sup>, F. Lanni<sup>24</sup>, K. Lantzschi<sup>173</sup>, S. Laplace<sup>77</sup>, C. Lapoire<sup>20</sup>, J.F. Laporte<sup>135</sup>, T. Lari<sup>88a</sup>, A.V. Larionov<sup>127</sup>, A. Larner<sup>117</sup>, C. Lasseur<sup>29</sup>, M. Lassnig<sup>29</sup>, P. Laurelli<sup>47</sup>, V. Lavorini<sup>36a,36b</sup>, W. Lavrijsen<sup>14</sup>, P. Laycock<sup>72</sup>, A.B. Lazarev<sup>64</sup>, O. Le Dortz<sup>77</sup>, E. Le Guirriec<sup>82</sup>, C. Le Maner<sup>157</sup>, E. Le Menedeu<sup>11</sup>, C. Lebel<sup>92</sup>, T. LeCompte<sup>5</sup>, F. Ledroit-Guillon<sup>55</sup>, H. Lee<sup>104</sup>, J.S.H. Lee<sup>115</sup>, S.C. Lee<sup>150</sup>, L. Lee<sup>174</sup>, M. Lefebvre<sup>168</sup>, M. Legendre<sup>135</sup>, A. Leger<sup>49</sup>, B.C. LeGeyt<sup>119</sup>, F. Legger<sup>97</sup>, C. Leggett<sup>14</sup>, M. Lehmacher<sup>20</sup>, G. Lehmann Miotto<sup>29</sup>, X. Lei<sup>6</sup>, M.A.L. Leite<sup>23d</sup>, R. Leitner<sup>125</sup>, D. Lellouch<sup>170</sup>, M. Leltchouk<sup>34</sup>, B. Lemmer<sup>54</sup>, V. Lendermann<sup>58a</sup>, K.J.C. Leney<sup>144b</sup>, T. Lenz<sup>104</sup>, G. Lenzen<sup>173</sup>, B. Lenzi<sup>29</sup>, K. Leonhardt<sup>43</sup>, S. Leontsinis<sup>9</sup>, C. Leroy<sup>92</sup>, J.-R. Lessard<sup>168</sup>, J. Lesser<sup>145a</sup>, C.G. Lester<sup>27</sup>, A. Leung Fook Cheong<sup>171</sup>, J. Levêque<sup>4</sup>, D. Levin<sup>86</sup>, L.J. Levinson<sup>170</sup>, M.S. Levitski<sup>127</sup>, A. Lewis<sup>117</sup>, G.H. Lewis<sup>107</sup>, A.M. Leyko<sup>20</sup>, M. Leyton<sup>15</sup>, B. Li<sup>82</sup>, H. Li<sup>171,s</sup>, S. Li<sup>32b,t</sup>, X. Li<sup>86</sup>, Z. Liang<sup>117,u</sup>, H. Liao<sup>33</sup>, B. Liberti<sup>132a</sup>, P. Lichard<sup>29</sup>, M. Lichtnecker<sup>97</sup>, K. Lie<sup>164</sup>, W. Liebig<sup>13</sup>, C. Limbach<sup>20</sup>, A. Limosani<sup>85</sup>, M. Limper<sup>62</sup>, S.C. Lin<sup>150,v</sup>, F. Linde<sup>104</sup>, J.T. Linnemann<sup>87</sup>, E. Lipeles<sup>119</sup>, L. Lipinsky<sup>124</sup>, A. Lipniacka<sup>13</sup>, T.M. Liss<sup>164</sup>, D. Lissauer<sup>24</sup>, A. Lister<sup>49</sup>, A.M. Litke<sup>136</sup>, C. Liu<sup>28</sup>, D. Liu<sup>150</sup>, H. Liu<sup>86</sup>, J.B. Liu<sup>86</sup>, M. Liu<sup>32b</sup>, Y. Liu<sup>32b</sup>, M. Livan<sup>118a,118b</sup>, S.S.A. Livermore<sup>117</sup>, A. Lleres<sup>55</sup>, J. Llorente Merino<sup>79</sup>, S.L. Lloyd<sup>74</sup>, E. Lobodzinska<sup>41</sup>, P. Loch<sup>6</sup>, W.S. Lockman<sup>136</sup>, T. Loddenkoetter<sup>20</sup>, F.K. Loebinger<sup>81</sup>, A. Loginov<sup>174</sup>, C.W. Loh<sup>167</sup>, T. Lohse<sup>15</sup>, K. Lohwasser<sup>48</sup>, M. Lokajicek<sup>124</sup>, J. Loken<sup>117</sup>, V.P. Lombardo<sup>4</sup>, R.E. Long<sup>70</sup>, L. Lopes<sup>123a</sup>, D. Lopez Mateos<sup>57</sup>, J. Lorenz<sup>97</sup>, N. Lorenzo Martinez<sup>114</sup>, M. Losada<sup>161</sup>, P. Loscutoff<sup>14</sup>, F. Lo Sterzo<sup>131a,131b</sup>, M.J. Losty<sup>158a</sup>, X. Lou<sup>40</sup>, A. Lounis<sup>114</sup>, K.F. Loureiro<sup>161</sup>, J. Love<sup>21</sup>, P.A. Love<sup>70</sup>, A.J. Lowe<sup>142,e</sup>, F. Lu<sup>32a</sup>, H.J. Lubatti<sup>137</sup>, C. Luci<sup>131a,131b</sup>, A. Lucotte<sup>55</sup>, A. Ludwig<sup>43</sup>, D. Ludwig<sup>41</sup>, I. Ludwig<sup>48</sup>, J. Ludwig<sup>48</sup>, F. Luehring<sup>60</sup>, G. Luijkx<sup>104</sup>, W. Lukas<sup>61</sup>, D. Lumb<sup>48</sup>, L. Luminari<sup>131a</sup>, E. Lund<sup>116</sup>, B. Lund-Jensen<sup>146</sup>, B. Lundberg<sup>78</sup>, J. Lundberg<sup>145a,145b</sup>, J. Lundquist<sup>35</sup>, M. Lungwitz<sup>80</sup>, G. Lutz<sup>98</sup>, D. Lynn<sup>24</sup>, J. Lys<sup>14</sup>, E. Lytken<sup>78</sup>, H. Ma<sup>24</sup>, L.L. Ma<sup>171</sup>, J.A. Macana Goia<sup>92</sup>, G. Maccarrone<sup>47</sup>, A. Macchiolo<sup>98</sup>, B. Maček<sup>73</sup>, J. Machado Miguens<sup>123a</sup>, R. Mackeprang<sup>35</sup>, R.J. Madaras<sup>14</sup>, W.F. Mader<sup>43</sup>, R. Maenner<sup>58c</sup>, T. Maeno<sup>24</sup>, P. Mättig<sup>173</sup>, S. Mättig<sup>41</sup>, L. Magnoni<sup>29</sup>, E. Magradze<sup>54</sup>, Y. Mahalalel<sup>152</sup>, K. Mahboubi<sup>48</sup>, S. Mahmoud<sup>72</sup>, G. Mahout<sup>17</sup>, C. Maiani<sup>131a,131b</sup>, C. Maidantchik<sup>23a</sup>, A. Maio<sup>123a,b</sup>, S. Majewski<sup>24</sup>, Y. Makida<sup>65</sup>, N. Makovec<sup>114</sup>, P. Mal<sup>135</sup>, B. Malaescu<sup>29</sup>, Pa. Malecki<sup>38</sup>, P. Malecki<sup>38</sup>, V.P. Maleev<sup>120</sup>, F. Malek<sup>55</sup>, U. Mallik<sup>62</sup>, D. Malon<sup>5</sup>, C. Malone<sup>142</sup>, S. Maltezos<sup>9</sup>, V. Malyshev<sup>106</sup>, S. Malyukov<sup>29</sup>, R. Mameghani<sup>97</sup>, J. Mamuzic<sup>12b</sup>, A. Manabe<sup>65</sup>, L. Mandelli<sup>88a</sup>, I. Mandić<sup>73</sup>, R. Mandrysch<sup>15</sup>, J. Maneira<sup>123a</sup>, P.S. Mangeard<sup>87</sup>, L. Manhaes de Andrade Filho<sup>23a</sup>, I.D. Manjavidze<sup>64</sup>, A. Mann<sup>54</sup>, P.M. Manning<sup>136</sup>,

A. Manousakis-Katsikakis<sup>8</sup>, B. Mansoulie<sup>135</sup>, A. Manz<sup>98</sup>, A. Mapelli<sup>29</sup>, L. Mapelli<sup>29</sup>, L. March<sup>79</sup>, J.F. Marchand<sup>28</sup>, F. Marchese<sup>132a,132b</sup>, G. Marchiori<sup>77</sup>, M. Marcisovsky<sup>124</sup>, C.P. Marino<sup>168</sup>, F. Marroquim<sup>23a</sup>, R. Marshall<sup>81</sup>, Z. Marshall<sup>29</sup>, F.K. Martens<sup>157</sup>, S. Marti-Garcia<sup>166</sup>, A.J. Martin<sup>174</sup>, B. Martin<sup>29</sup>, B. Martin<sup>87</sup>, F.F. Martin<sup>119</sup>, J.P. Martin<sup>92</sup>, Ph. Martin<sup>55</sup>, T.A. Martin<sup>17</sup>, V.J. Martin<sup>45</sup>, B. Martin dit Latour<sup>49</sup>, S. Martin-Haugh<sup>148</sup>, M. Martinez<sup>11</sup>, V. Martinez Outschoorn<sup>57</sup>, A.C. Martyniuk<sup>168</sup>, M. Marx<sup>81</sup>, F. Marzano<sup>131a</sup>, A. Marzin<sup>110</sup>, L. Masetti<sup>80</sup>, T. Mashimo<sup>154</sup>, R. Mashinistov<sup>93</sup>, J. Masik<sup>81</sup>, A.L. Maslennikov<sup>106</sup>, I. Massa<sup>19a,19b</sup>, G. Massaro<sup>104</sup>, N. Massol<sup>4</sup>, P. Mastrandrea<sup>131a,131b</sup>, A. Mastroberardino<sup>36a,36b</sup>, T. Masubuchi<sup>154</sup>, P. Matricon<sup>114</sup>, H. Matsumoto<sup>154</sup>, H. Matsunaga<sup>154</sup>, T. Matsushita<sup>66</sup>, C. Mattravers<sup>117,c</sup>, J.M. Maugain<sup>29</sup>, J. Maurer<sup>82</sup>, S.J. Maxfield<sup>72</sup>, D.A. Maximov<sup>106,f</sup>, E.N. May<sup>5</sup>, A. Mayne<sup>138</sup>, R. Mazini<sup>150</sup>, M. Mazur<sup>20</sup>, M. Mazzanti<sup>88a</sup>, S.P. Mc Kee<sup>86</sup>, A. McCarn<sup>164</sup>, R.L. McCarthy<sup>147</sup>, T.G. McCarthy<sup>28</sup>, N.A. McCubbin<sup>128</sup>, K.W. McFarlane<sup>56</sup>, J.A. Mcfayden<sup>138</sup>, H. McGlone<sup>53</sup>, G. Mchedlidze<sup>51b</sup>, R.A. McLaren<sup>29</sup>, T. McLaughlan<sup>17</sup>, S.J. McMahon<sup>128</sup>, R.A. McPherson<sup>168,j</sup>, A. Meade<sup>83</sup>, J. Mechnich<sup>104</sup>, M. Mechtel<sup>173</sup>, M. Medinnis<sup>41</sup>, R. Meera-Lebbai<sup>110</sup>, T. Meguro<sup>115</sup>, R. Mehdiyev<sup>92</sup>, S. Mehlhase<sup>35</sup>, A. Mehta<sup>72</sup>, K. Meier<sup>58a</sup>, B. Meirose<sup>78</sup>, C. Melachrinou<sup>30</sup>, B.R. Mellado Garcia<sup>171</sup>, L. Mendoza Navas<sup>161</sup>, Z. Meng<sup>150,s</sup>, A. Mengarelli<sup>19a,19b</sup>, S. Menke<sup>98</sup>, C. Menot<sup>29</sup>, E. Meoni<sup>11</sup>, K.M. Mercurio<sup>57</sup>, P. Mermoud<sup>49</sup>, L. Merola<sup>101a,101b</sup>, C. Meroni<sup>88a</sup>, F.S. Merritt<sup>30</sup>, H. Merritt<sup>108</sup>, A. Messina<sup>29</sup>, J. Metcalfe<sup>102</sup>, A.S. Mete<sup>63</sup>, C. Meyer<sup>80</sup>, C. Meyer<sup>30</sup>, J-P. Meyer<sup>135</sup>, J. Meyer<sup>172</sup>, J. Meyer<sup>54</sup>, T.C. Meyer<sup>29</sup>, W.T. Meyer<sup>63</sup>, J. Miao<sup>32d</sup>, S. Michal<sup>29</sup>, L. Micu<sup>25a</sup>, R.P. Middleton<sup>128</sup>, S. Migas<sup>72</sup>, L. Mijović<sup>41</sup>, G. Mikenberg<sup>170</sup>, M. Mikestikova<sup>124</sup>, M. Mikuž<sup>73</sup>, D.W. Miller<sup>30</sup>, R.J. Miller<sup>87</sup>, W.J. Mills<sup>167</sup>, C. Mills<sup>57</sup>, A. Milov<sup>170</sup>, D.A. Milstead<sup>145a,145b</sup>, D. Milstein<sup>170</sup>, A.A. Minaenko<sup>127</sup>, M. Miñano Moya<sup>166</sup>, I.A. Minashvili<sup>64</sup>, A.I. Mincer<sup>107</sup>, B. Mindur<sup>37</sup>, M. Mineev<sup>64</sup>, Y. Ming<sup>171</sup>, L.M. Mir<sup>11</sup>, G. Mirabelli<sup>131a</sup>, L. Miralles Verge<sup>11</sup>, A. Misiejuk<sup>75</sup>, J. Mitrevski<sup>136</sup>, G.Y. Mitrofanov<sup>127</sup>, V.A. Mitsou<sup>166</sup>, S. Mitsui<sup>65</sup>, P.S. Miyagawa<sup>138</sup>, K. Miyazaki<sup>66</sup>, J.U. Mjörnmark<sup>78</sup>, T. Moa<sup>145a,145b</sup>, P. Mockett<sup>137</sup>, S. Moed<sup>57</sup>, V. Moeller<sup>27</sup>, K. Mönig<sup>41</sup>, N. Möser<sup>20</sup>, S. Mohapatra<sup>147</sup>, W. Mohr<sup>48</sup>, S. Mohr dieck-Möck<sup>98</sup>, R. Moles-Valls<sup>166</sup>, J. Molina-Perez<sup>29</sup>, J. Monk<sup>76</sup>, E. Monnier<sup>82</sup>, S. Montesano<sup>88a,88b</sup>, F. Monticelli<sup>69</sup>, S. Monzani<sup>19a,19b</sup>, R.W. Moore<sup>2</sup>, G.F. Moorhead<sup>85</sup>, C. Mora Herrera<sup>49</sup>, A. Moraes<sup>53</sup>, N. Morange<sup>135</sup>, J. Morel<sup>54</sup>, G. Morello<sup>36a,36b</sup>, D. Moreno<sup>80</sup>, M. Moreno Llácer<sup>166</sup>, P. Morettini<sup>50a</sup>, M. Morgenstern<sup>43</sup>, M. Morii<sup>57</sup>, J. Morin<sup>74</sup>, A.K. Morley<sup>29</sup>, G. Mornacchi<sup>29</sup>, S.V. Morozov<sup>95</sup>, J.D. Morris<sup>74</sup>, L. Morvaj<sup>100</sup>, H.G. Moser<sup>98</sup>, M. Mosidze<sup>51b</sup>, J. Moss<sup>108</sup>, R. Mount<sup>142</sup>, E. Mountricha<sup>9,w</sup>, S.V. Mouraviev<sup>93</sup>, E.J.W. Moyse<sup>83</sup>, M. Mudrinic<sup>12b</sup>, F. Mueller<sup>58a</sup>, J. Mueller<sup>122</sup>, K. Mueller<sup>20</sup>, T.A. Müller<sup>97</sup>, T. Mueller<sup>80</sup>, D. Muenstermann<sup>29</sup>, A. Muir<sup>167</sup>, Y. Munwes<sup>152</sup>, W.J. Murray<sup>128</sup>, I. Mussche<sup>104</sup>, E. Musto<sup>101a,101b</sup>, A.G. Myagkov<sup>127</sup>, M. Myska<sup>124</sup>, J. Nadal<sup>11</sup>, K. Nagai<sup>159</sup>, K. Nagano<sup>65</sup>, A. Nagarkar<sup>108</sup>, Y. Nagasaka<sup>59</sup>, M. Nagel<sup>98</sup>, A.M. Nairz<sup>29</sup>, Y. Nakahama<sup>29</sup>, K. Nakamura<sup>154</sup>, T. Nakamura<sup>154</sup>, I. Nakano<sup>109</sup>, G. Nanava<sup>20</sup>, A. Napier<sup>160</sup>, R. Narayan<sup>58b</sup>, M. Nash<sup>76,c</sup>, N.R. Nation<sup>21</sup>, T. Nattermann<sup>20</sup>, T. Naumann<sup>41</sup>, G. Navarro<sup>161</sup>, H.A. Neal<sup>86</sup>, E. Nebot<sup>79</sup>, P.Yu. Nechaeva<sup>93</sup>, T.J. Neep<sup>81</sup>, A. Negri<sup>118a,118b</sup>, G. Negri<sup>29</sup>, S. Nektarijevic<sup>49</sup>, A. Nelson<sup>162</sup>, T.K. Nelson<sup>142</sup>, S. Nemecek<sup>124</sup>, P. Nemethy<sup>107</sup>, A.A. Nepomuceno<sup>23a</sup>, M. Nessi<sup>29,x</sup>, M.S. Neubauer<sup>164</sup>, A. Neusiedl<sup>80</sup>, R.M. Neves<sup>107</sup>, P. Nevski<sup>24</sup>, P.R. Newman<sup>17</sup>, V. Nguyen Thi Hong<sup>135</sup>, R.B. Nickerson<sup>117</sup>, R. Nicolaidou<sup>135</sup>, L. Nicolas<sup>138</sup>, B. Nicquevert<sup>29</sup>, F. Niedercorn<sup>114</sup>, J. Nielsen<sup>136</sup>, T. Niinikoski<sup>29</sup>, N. Nikiforou<sup>34</sup>, A. Nikiforov<sup>15</sup>, V. Nikolaenko<sup>127</sup>, K. Nikolaev<sup>64</sup>, I. Nikolic-Audit<sup>77</sup>, K. Nikolics<sup>49</sup>, K. Nikolopoulos<sup>24</sup>, H. Nilsen<sup>48</sup>, P. Nilsson<sup>7</sup>, Y. Ninomiya<sup>154</sup>, A. Nisati<sup>131a</sup>, T. Nishiyama<sup>66</sup>, R. Nisius<sup>98</sup>, L. Nodulman<sup>5</sup>, M. Nomachi<sup>115</sup>, I. Nomidis<sup>153</sup>, M. Nordberg<sup>29</sup>, P.R. Norton<sup>128</sup>, J. Novakova<sup>125</sup>, M. Nozaki<sup>65</sup>, L. Nozka<sup>112</sup>, I.M. Nugent<sup>158a</sup>, A.-E. Nuncio-Quiroz<sup>20</sup>, G. Nunes Hanninger<sup>85</sup>, T. Nunnemann<sup>97</sup>, E. Nurse<sup>76</sup>, B.J. O'Brien<sup>45</sup>, S.W. O'Neale<sup>17,\*</sup>, D.C. O'Neil<sup>141</sup>, V. O'Shea<sup>53</sup>, L.B. Oakes<sup>97</sup>, F.G. Oakham<sup>28,d</sup>, H. Oberlack<sup>98</sup>, J. Ocariz<sup>77</sup>, A. Ochi<sup>66</sup>, S. Oda<sup>154</sup>, S. Odaka<sup>65</sup>, J. Odier<sup>82</sup>, H. Ogren<sup>60</sup>, A. Oh<sup>81</sup>, S.H. Oh<sup>44</sup>, C.C. Ohm<sup>145a,145b</sup>, T. Ohshima<sup>100</sup>, H. Ohshita<sup>139</sup>, S. Okada<sup>66</sup>, H. Okawa<sup>162</sup>, Y. Okumura<sup>100</sup>, T. Okuyama<sup>154</sup>, A. Olariu<sup>25a</sup>, M. Olcese<sup>50a</sup>, A.G. Olchevski<sup>64</sup>, S.A. Olivares Pino<sup>31a</sup>, M. Oliveira<sup>123a,h</sup>, D. Oliveira Damazio<sup>24</sup>, E. Oliver Garcia<sup>166</sup>, D. Olivito<sup>119</sup>, A. Olszewski<sup>38</sup>, J. Olszowska<sup>38</sup>, C. Omachi<sup>66</sup>, A. Onofre<sup>123a,y</sup>, P.U.E. Onyisi<sup>30</sup>, C.J. Oram<sup>158a</sup>, M.J. Oreglia<sup>30</sup>, Y. Oren<sup>152</sup>, D. Orestano<sup>133a,133b</sup>, N. Orlando<sup>71a,71b</sup>, I. Orlov<sup>106</sup>, C. Oropeza Barrera<sup>53</sup>, R.S. Orr<sup>157</sup>, B. Osculati<sup>50a,50b</sup>, R. Ospanov<sup>119</sup>, C. Osuna<sup>11</sup>, G. Otero y Garzon<sup>26</sup>, J.P. Ottersbach<sup>104</sup>, M. Ouchrif<sup>134d</sup>, E.A. Ouellette<sup>168</sup>, F. Ould-Saada<sup>116</sup>, A. Ouraou<sup>135</sup>, Q. Ouyang<sup>32a</sup>, A. Ovcharova<sup>14</sup>, M. Owen<sup>81</sup>, S. Owen<sup>138</sup>, V.E. Ozcan<sup>18a</sup>,



N. Ozturk<sup>7</sup>, A. Pacheco Pages<sup>11</sup>, C. Padilla Aranda<sup>11</sup>, S. Pagan Griso<sup>14</sup>, E. Paganis<sup>138</sup>, F. Paige<sup>24</sup>, P. Pais<sup>83</sup>, K. Pajchel<sup>116</sup>, G. Palacino<sup>158b</sup>, C.P. Paleari<sup>6</sup>, S. Palestini<sup>29</sup>, D. Pallin<sup>33</sup>, A. Palma<sup>123a</sup>, J.D. Palmer<sup>17</sup>, Y.B. Pan<sup>171</sup>, E. Panagiotopoulou<sup>9</sup>, B. Panes<sup>31a</sup>, N. Panikashvili<sup>86</sup>, S. Panitkin<sup>24</sup>, D. Pantea<sup>25a</sup>, M. Panuskova<sup>124</sup>, V. Paolone<sup>122</sup>, A. Papadelis<sup>145a</sup>, Th.D. Papadopoulou<sup>9</sup>, A. Paramonov<sup>5</sup>, D. Paredes Hernandez<sup>33</sup>, W. Park<sup>24,z</sup>, M.A. Parker<sup>27</sup>, F. Parodi<sup>50a,50b</sup>, J.A. Parsons<sup>34</sup>, U. Parzefall<sup>48</sup>, S. Pashapour<sup>54</sup>, E. Pasqualucci<sup>131a</sup>, S. Passaggio<sup>50a</sup>, A. Passeri<sup>133a</sup>, F. Pastore<sup>133a,133b</sup>, Fr. Pastore<sup>75</sup>, G. Pásztor<sup>49,aa</sup>, S. Pataraiia<sup>173</sup>, N. Patel<sup>149</sup>, J.R. Pater<sup>81</sup>, S. Patricelli<sup>101a,101b</sup>, T. Pauly<sup>29</sup>, M. Pecsý<sup>143a</sup>, M.I. Pedraza Morales<sup>171</sup>, S.V. Peleganchuk<sup>106</sup>, H. Peng<sup>32b</sup>, B. Penning<sup>30</sup>, A. Penson<sup>34</sup>, J. Penwell<sup>60</sup>, M. Perantoni<sup>23a</sup>, K. Perez<sup>34,ab</sup>, T. Perez Cavalcanti<sup>41</sup>, E. Perez Codina<sup>158a</sup>, M.T. Pérez García-Estañ<sup>166</sup>, V. Perez Reale<sup>34</sup>, L. Perini<sup>88a,88b</sup>, H. Pernegger<sup>29</sup>, R. Perrino<sup>71a</sup>, P. Perrodo<sup>4</sup>, S. Persema<sup>3a</sup>, V.D. Peshekhonov<sup>64</sup>, K. Peters<sup>29</sup>, B.A. Petersen<sup>29</sup>, J. Petersen<sup>29</sup>, T.C. Petersen<sup>35</sup>, E. Petit<sup>4</sup>, A. Petridis<sup>153</sup>, C. Petridou<sup>153</sup>, E. Petrolo<sup>131a</sup>, F. Petrucci<sup>133a,133b</sup>, D. Petschall<sup>41</sup>, M. Petteni<sup>141</sup>, R. Pezoa<sup>31b</sup>, A. Phan<sup>85</sup>, P.W. Phillips<sup>128</sup>, G. Piacquadio<sup>29</sup>, A. Picazio<sup>49</sup>, E. Piccaro<sup>74</sup>, M. Piccinini<sup>19a,19b</sup>, S.M. Piec<sup>41</sup>, R. Piegaiia<sup>26</sup>, D.T. Pignotti<sup>108</sup>, J.E. Pilcher<sup>30</sup>, A.D. Pilkington<sup>81</sup>, J. Pina<sup>123a,b</sup>, M. Pinamonti<sup>163a,163c</sup>, A. Pinder<sup>117</sup>, J.L. Pinfold<sup>2</sup>, J. Ping<sup>32c</sup>, B. Pinto<sup>123a</sup>, O. Pirotte<sup>29</sup>, C. Pizio<sup>88a,88b</sup>, M. Plamondon<sup>168</sup>, M.-A. Pleier<sup>24</sup>, A.V. Pleskach<sup>127</sup>, E. Plotnikova<sup>64</sup>, A. Poblaguev<sup>24</sup>, S. Poddar<sup>58a</sup>, F. Podlyski<sup>33</sup>, L. Poggioli<sup>114</sup>, T. Poghosyan<sup>20</sup>, M. Pohl<sup>49</sup>, F. Polci<sup>55</sup>, G. Polesello<sup>118a</sup>, A. Policicchio<sup>36a,36b</sup>, A. Polini<sup>19a</sup>, J. Poll<sup>74</sup>, V. Polychronakos<sup>24</sup>, D.M. Pomarede<sup>135</sup>, D. Pomeroy<sup>22</sup>, K. Pommès<sup>29</sup>, L. Pontecorvo<sup>131a</sup>, B.G. Pope<sup>87</sup>, G.A. Popeneciu<sup>25a</sup>, D.S. Popovic<sup>12a</sup>, A. Poppleton<sup>29</sup>, X. Portell Bueso<sup>29</sup>, C. Posch<sup>21</sup>, G.E. Pospelov<sup>98</sup>, S. Pospisil<sup>126</sup>, I.N. Potrap<sup>98</sup>, C.J. Potter<sup>148</sup>, C.T. Potter<sup>113</sup>, G. Poulard<sup>29</sup>, J. Poveda<sup>171</sup>, V. Pozdnyakov<sup>64</sup>, R. Prabhu<sup>76</sup>, P. Pralavorio<sup>82</sup>, A. Pranko<sup>14</sup>, S. Prasad<sup>29</sup>, R. Pravahan<sup>7</sup>, S. Prell<sup>63</sup>, K. Pretzl<sup>16</sup>, L. Pribyl<sup>29</sup>, D. Price<sup>60</sup>, J. Price<sup>72</sup>, L.E. Price<sup>5</sup>, M.J. Price<sup>29</sup>, D. Prieur<sup>122</sup>, M. Primavera<sup>71a</sup>, K. Prokofiev<sup>107</sup>, F. Prokoshin<sup>31b</sup>, S. Protopopescu<sup>24</sup>, J. Proudfoot<sup>5</sup>, X. Prudent<sup>43</sup>, M. Przybycien<sup>37</sup>, H. Przysiezniak<sup>4</sup>, S. Psoroulas<sup>20</sup>, E. Ptacek<sup>113</sup>, E. Pueschel<sup>83</sup>, J. Purdham<sup>86</sup>, M. Purohit<sup>24,z</sup>, P. Puzo<sup>114</sup>, Y. Pylypchenko<sup>62</sup>, J. Qian<sup>86</sup>, Z. Qian<sup>82</sup>, Z. Qin<sup>41</sup>, A. Quadt<sup>54</sup>, D.R. Quarrie<sup>14</sup>, W.B. Quayle<sup>171</sup>, F. Quinonez<sup>31a</sup>, M. Raas<sup>103</sup>, V. Radescu<sup>41</sup>, B. Radics<sup>20</sup>, P. Radloff<sup>113</sup>, T. Rador<sup>18a</sup>, F. Ragusa<sup>88a,88b</sup>, G. Rahal<sup>176</sup>, A.M. Rahimi<sup>108</sup>, D. Rahm<sup>24</sup>, S. Rajagopalan<sup>24</sup>, M. Rammensee<sup>48</sup>, M. Rammes<sup>140</sup>, A.S. Randle-Conde<sup>39</sup>, K. Randrianarivony<sup>28</sup>, P.N. Ratoff<sup>70</sup>, F. Rauscher<sup>97</sup>, T.C. Rave<sup>48</sup>, M. Raymond<sup>29</sup>, A.L. Read<sup>116</sup>, D.M. Rebuzzi<sup>118a,118b</sup>, A. Redelbach<sup>172</sup>, G. Redlinger<sup>24</sup>, R. Reece<sup>119</sup>, K. Reeves<sup>40</sup>, A. Reichold<sup>104</sup>, E. Reinherz-Aronis<sup>152</sup>, A. Reinsch<sup>113</sup>, I. Reisinger<sup>42</sup>, C. Rembser<sup>29</sup>, Z.L. Ren<sup>150</sup>, A. Renaud<sup>114</sup>, M. Rescigno<sup>131a</sup>, S. Resconi<sup>88a</sup>, B. Resende<sup>135</sup>, P. Reznicek<sup>97</sup>, R. Rezvani<sup>157</sup>, A. Richards<sup>76</sup>, R. Richter<sup>98</sup>, E. Richter-Was<sup>4,ac</sup>, M. Ridel<sup>77</sup>, M. Rijpstra<sup>104</sup>, M. Rijssenbeek<sup>147</sup>, A. Rimoldi<sup>118a,118b</sup>, L. Rinaldi<sup>19a</sup>, R.R. Rios<sup>39</sup>, I. Riu<sup>11</sup>, G. Rivoltella<sup>88a,88b</sup>, F. Rizatdinova<sup>111</sup>, E. Rizvi<sup>74</sup>, S.H. Robertson<sup>84,j</sup>, A. Robichaud-Veronneau<sup>117</sup>, D. Robinson<sup>27</sup>, J.E.M. Robinson<sup>76</sup>, A. Robson<sup>53</sup>, J.G. Rocha de Lima<sup>105</sup>, C. Roda<sup>121a,121b</sup>, D. Roda Dos Santos<sup>29</sup>, D. Rodriguez<sup>161</sup>, A. Roe<sup>54</sup>, S. Roe<sup>29</sup>, O. Røhne<sup>116</sup>, V. Rojo<sup>1</sup>, S. Rolli<sup>160</sup>, A. Romaniouk<sup>95</sup>, M. Romano<sup>19a,19b</sup>, V.M. Romanov<sup>64</sup>, G. Romeo<sup>26</sup>, E. Romero Adam<sup>166</sup>, L. Roos<sup>77</sup>, E. Ros<sup>166</sup>, S. Rosati<sup>131a</sup>, K. Rosbach<sup>49</sup>, A. Rose<sup>148</sup>, M. Rose<sup>75</sup>, G.A. Rosenbaum<sup>157</sup>, E.I. Rosenberg<sup>63</sup>, P.L. Rosendahl<sup>13</sup>, O. Rosenthal<sup>140</sup>, L. Rosselet<sup>49</sup>, V. Rossetti<sup>11</sup>, E. Rossi<sup>131a,131b</sup>, L.P. Rossi<sup>50a</sup>, M. Rotaru<sup>25a</sup>, I. Roth<sup>170</sup>, J. Rothberg<sup>137</sup>, D. Rousseau<sup>114</sup>, C.R. Royon<sup>135</sup>, A. Rozanov<sup>82</sup>, Y. Rozen<sup>151</sup>, X. Ruan<sup>32a,ad</sup>, F. Rubbo<sup>11</sup>, I. Rubinskiy<sup>41</sup>, B. Ruckert<sup>97</sup>, N. Ruckstuhl<sup>104</sup>, V.I. Rud<sup>96</sup>, C. Rudolph<sup>43</sup>, G. Rudolph<sup>61</sup>, F. Rühr<sup>6</sup>, F. Ruggieri<sup>133a,133b</sup>, A. Ruiz-Martinez<sup>63</sup>, V. Rumiantsev<sup>90,\*</sup>, L. Rumyantsev<sup>64</sup>, K. Runge<sup>48</sup>, Z. Rurikova<sup>48</sup>, N.A. Rusakovich<sup>64</sup>, J.P. Rutherford<sup>6</sup>, C. Ruwiedel<sup>14</sup>, P. Ruzicka<sup>124</sup>, Y.F. Ryabov<sup>120</sup>, V. Ryadovikov<sup>127</sup>, P. Ryan<sup>87</sup>, M. Rybar<sup>125</sup>, G. Rybkin<sup>114</sup>, N.C. Ryder<sup>117</sup>, S. Rzaeva<sup>10</sup>, A.F. Saavedra<sup>149</sup>, I. Sadeh<sup>152</sup>, H.F.W. Sadrozinski<sup>136</sup>, R. Sadykov<sup>64</sup>, F. Safai Tehrani<sup>131a</sup>, H. Sakamoto<sup>154</sup>, G. Salamanna<sup>74</sup>, A. Salamon<sup>132a</sup>, M. Saleem<sup>110</sup>, D. Salek<sup>29</sup>, D. Salihagic<sup>98</sup>, A. Salnikov<sup>142</sup>, J. Salt<sup>166</sup>, B.M. Salvachua Ferrando<sup>5</sup>, D. Salvatore<sup>36a,36b</sup>, F. Salvatore<sup>148</sup>, A. Salvucci<sup>103</sup>, A. Salzburger<sup>29</sup>, D. Sampsonidis<sup>153</sup>, B.H. Samset<sup>116</sup>, A. Sanchez<sup>101a,101b</sup>, V. Sanchez Martinez<sup>166</sup>, H. Sandaker<sup>13</sup>, H.G. Sander<sup>80</sup>, M.P. Sanders<sup>97</sup>, M. Sandhoff<sup>173</sup>, T. Sandoval<sup>27</sup>, C. Sandoval<sup>161</sup>, R. Sandstroem<sup>98</sup>, S. Sandvoss<sup>173</sup>, D.P.C. Sankey<sup>128</sup>, A. Sansoni<sup>47</sup>, C. Santamarina Rios<sup>84</sup>, C. Santoni<sup>33</sup>, R. Santonico<sup>132a,132b</sup>, H. Santos<sup>123a</sup>, J.G. Saraiva<sup>123a</sup>, T. Sarangi<sup>171</sup>, E. Sarkisyan-Grinbaum<sup>7</sup>, F. Sarri<sup>121a,121b</sup>, G. Sartisohn<sup>173</sup>, O. Sasaki<sup>65</sup>, N. Sasao<sup>67</sup>, I. Satsounkevitch<sup>89</sup>, G. Sauvage<sup>4</sup>, E. Sauvan<sup>4</sup>, J.B. Sauvan<sup>114</sup>, P. Savard<sup>157,d</sup>, V. Savinov<sup>122</sup>, D.O. Savu<sup>29</sup>, L. Sawyer<sup>24,l</sup>, D.H. Saxon<sup>53</sup>, J. Saxon<sup>119</sup>,

L.P. Says<sup>33</sup>, C. Sbarra<sup>19a</sup>, A. Sbrizzi<sup>19a,19b</sup>, O. Scallan<sup>92</sup>, D.A. Scannicchio<sup>162</sup>, M. Scarcella<sup>149</sup>, J. Schaarschmidt<sup>114</sup>, P. Schacht<sup>98</sup>, D. Schaefer<sup>119</sup>, U. Schäfer<sup>80</sup>, S. Schaepe<sup>20</sup>, S. Schaetzel<sup>58b</sup>, A.C. Schaffer<sup>114</sup>, D. Schaile<sup>97</sup>, R.D. Schamberger<sup>147</sup>, A.G. Schamov<sup>106</sup>, V. Scharf<sup>58a</sup>, V.A. Schegelsky<sup>120</sup>, D. Scheirich<sup>86</sup>, M. Schernau<sup>162</sup>, M.I. Scherzer<sup>34</sup>, C. Schiavi<sup>50a,50b</sup>, J. Schieck<sup>97</sup>, M. Schioppa<sup>36a,36b</sup>, S. Schlenker<sup>29</sup>, J.L. Schlereth<sup>5</sup>, E. Schmidt<sup>48</sup>, K. Schmieden<sup>20</sup>, C. Schmitt<sup>80</sup>, S. Schmitt<sup>58b</sup>, M. Schmitz<sup>20</sup>, A. Schöning<sup>58b</sup>, M. Schott<sup>29</sup>, D. Schouten<sup>158a</sup>, J. Schovancova<sup>124</sup>, M. Schram<sup>84</sup>, C. Schroeder<sup>80</sup>, N. Schroer<sup>58c</sup>, G. Schuler<sup>29</sup>, M.J. Schultens<sup>20</sup>, J. Schultes<sup>173</sup>, H.-C. Schultz-Coulon<sup>58a</sup>, H. Schulz<sup>15</sup>, J.W. Schumacher<sup>20</sup>, M. Schumacher<sup>48</sup>, B.A. Schumm<sup>136</sup>, Ph. Schune<sup>135</sup>, C. Schwanenberger<sup>81</sup>, A. Schwartzman<sup>142</sup>, Ph. Schwemling<sup>77</sup>, R. Schwienhorst<sup>87</sup>, R. Schwierz<sup>43</sup>, J. Schwindling<sup>135</sup>, T. Schwindt<sup>20</sup>, M. Schwoerer<sup>4</sup>, G. Sciolla<sup>22</sup>, W.G. Scott<sup>128</sup>, J. Searcy<sup>113</sup>, G. Sedov<sup>41</sup>, E. Sedykh<sup>120</sup>, E. Segura<sup>11</sup>, S.C. Seidel<sup>102</sup>, A. Seiden<sup>136</sup>, F. Seifert<sup>43</sup>, J.M. Seixas<sup>23a</sup>, G. Sekhniaidze<sup>101a</sup>, S.J. Sekula<sup>39</sup>, K.E. Selbach<sup>45</sup>, D.M. Seliverstov<sup>120</sup>, B. Sellden<sup>145a</sup>, G. Sellers<sup>72</sup>, M. Seman<sup>143b</sup>, N. Semprini-Cesari<sup>19a,19b</sup>, C. Serfon<sup>97</sup>, L. Serin<sup>114</sup>, L. Serkin<sup>54</sup>, R. Seuster<sup>98</sup>, H. Severini<sup>110</sup>, M.E. Sevier<sup>85</sup>, A. Sfyrta<sup>29</sup>, E. Shabalina<sup>54</sup>, M. Shamim<sup>113</sup>, L.Y. Shan<sup>32a</sup>, J.T. Shank<sup>21</sup>, Q.T. Shao<sup>85</sup>, M. Shapiro<sup>14</sup>, P.B. Shatalov<sup>94</sup>, L. Shaver<sup>6</sup>, K. Shaw<sup>163a,163c</sup>, D. Sherman<sup>174</sup>, P. Sherwood<sup>76</sup>, A. Shibata<sup>107</sup>, H. Shichi<sup>100</sup>, S. Shimizu<sup>29</sup>, M. Shimojima<sup>99</sup>, T. Shin<sup>56</sup>, M. Shiyakova<sup>64</sup>, A. Shmeleva<sup>93</sup>, M.J. Shochet<sup>30</sup>, D. Short<sup>117</sup>, S. Shrestha<sup>63</sup>, E. Shulga<sup>95</sup>, M.A. Shupe<sup>6</sup>, P. Sicho<sup>124</sup>, A. Sidoti<sup>131a</sup>, F. Siegert<sup>48</sup>, Dj. Sijacki<sup>12a</sup>, O. Silbert<sup>170</sup>, J. Silva<sup>123a</sup>, Y. Silver<sup>152</sup>, D. Silverstein<sup>142</sup>, S.B. Silverstein<sup>145a</sup>, V. Simak<sup>126</sup>, O. Simard<sup>135</sup>, Lj. Simic<sup>12a</sup>, S. Simion<sup>114</sup>, B. Simmons<sup>76</sup>, R. Simoniello<sup>88a,88b</sup>, M. Simonyan<sup>35</sup>, P. Sinervo<sup>157</sup>, N.B. Sinev<sup>113</sup>, V. Sipica<sup>140</sup>, G. Siragusa<sup>172</sup>, A. Sircar<sup>24</sup>, A.N. Sisakyan<sup>64</sup>, S.Yu. Sivoklov<sup>96</sup>, J. Sjölin<sup>145a,145b</sup>, T.B. Sjursen<sup>13</sup>, L.A. Skinnari<sup>14</sup>, H.P. Skottowe<sup>57</sup>, K. Skovpen<sup>106</sup>, P. Skubic<sup>110</sup>, N. Skvorodnev<sup>22</sup>, M. Slater<sup>17</sup>, T. Slavicek<sup>126</sup>, K. Sliwa<sup>160</sup>, J. Sloper<sup>29</sup>, V. Smakhtin<sup>170</sup>, B.H. Smart<sup>45</sup>, S.Yu. Smirnov<sup>95</sup>, Y. Smirnov<sup>95</sup>, L.N. Smirnova<sup>96</sup>, O. Smirnova<sup>78</sup>, B.C. Smith<sup>57</sup>, D. Smith<sup>142</sup>, K.M. Smith<sup>53</sup>, M. Smizanska<sup>70</sup>, K. Smolek<sup>126</sup>, A.A. Snesarev<sup>93</sup>, S.W. Snow<sup>81</sup>, J. Snow<sup>110</sup>, J. Snuverink<sup>104</sup>, S. Snyder<sup>24</sup>, M. Soares<sup>123a</sup>, R. Sobie<sup>168,j</sup>, J. Sodomka<sup>126</sup>, A. Soffer<sup>152</sup>, C.A. Solans<sup>166</sup>, M. Solar<sup>126</sup>, J. Solc<sup>126</sup>, E. Soldatov<sup>95</sup>, U. Soldevila<sup>166</sup>, E. Solfaroli Camillocci<sup>131a,131b</sup>, A.A. Solodkov<sup>127</sup>, O.V. Solovyanov<sup>127</sup>, N. Soni<sup>2</sup>, V. Sopko<sup>126</sup>, B. Sopko<sup>126</sup>, M. Sosebee<sup>7</sup>, R. Soualah<sup>163a,163c</sup>, A. Soukharev<sup>106</sup>, S. Spagnolo<sup>71a,71b</sup>, F. Spanò<sup>75</sup>, R. Spighi<sup>19a</sup>, G. Spigo<sup>29</sup>, F. Spila<sup>131a,131b</sup>, R. Spiwoks<sup>29</sup>, M. Spousta<sup>125</sup>, T. Spreitzer<sup>157</sup>, B. Spurlock<sup>7</sup>, R.D. St. Denis<sup>53</sup>, J. Stahlman<sup>119</sup>, R. Stamen<sup>58a</sup>, E. Stanecka<sup>38</sup>, R.W. Stanek<sup>5</sup>, C. Stancu<sup>133a</sup>, M. Stancu-Bellu<sup>41</sup>, S. Stapnes<sup>116</sup>, E.A. Starchenko<sup>127</sup>, J. Stark<sup>55</sup>, P. Staroba<sup>124</sup>, P. Starovoitov<sup>90</sup>, A. Staude<sup>97</sup>, P. Stavina<sup>143a</sup>, G. Steele<sup>53</sup>, P. Steinbach<sup>43</sup>, P. Steinberg<sup>24</sup>, I. Stekl<sup>126</sup>, B. Stelzer<sup>141</sup>, H.J. Stelzer<sup>87</sup>, O. Stelzer-Chilton<sup>158a</sup>, H. Stenzel<sup>52</sup>, S. Stern<sup>98</sup>, K. Stevenson<sup>74</sup>, G.A. Stewart<sup>29</sup>, J.A. Stillings<sup>20</sup>, M.C. Stockton<sup>84</sup>, K. Stoerig<sup>48</sup>, G. Stoicea<sup>25a</sup>, S. Stonjek<sup>98</sup>, P. Strachota<sup>125</sup>, A.R. Stradling<sup>7</sup>, A. Straessner<sup>43</sup>, J. Strandberg<sup>146</sup>, S. Strandberg<sup>145a,145b</sup>, A. Strandlie<sup>116</sup>, M. Strang<sup>108</sup>, E. Strauss<sup>142</sup>, M. Strauss<sup>110</sup>, P. Strizenec<sup>143b</sup>, R. Ströhmer<sup>172</sup>, D.M. Strom<sup>113</sup>, J.A. Strong<sup>75,\*</sup>, R. Stroynowski<sup>39</sup>, J. Strube<sup>128</sup>, B. Stugu<sup>13</sup>, I. Stumer<sup>24,\*</sup>, J. Stupak<sup>147</sup>, P. Sturm<sup>173</sup>, N.A. Styles<sup>41</sup>, D.A. Soh<sup>150,u</sup>, D. Su<sup>142</sup>, H.S. Subramania<sup>2</sup>, A. Succurro<sup>11</sup>, Y. Sugaya<sup>115</sup>, T. Sugimoto<sup>100</sup>, C. Suhr<sup>105</sup>, K. Suita<sup>66</sup>, M. Suk<sup>125</sup>, V.V. Sulin<sup>93</sup>, S. Sultansoy<sup>3d</sup>, T. Sumida<sup>67</sup>, X. Sun<sup>55</sup>, J.E. Sundermann<sup>48</sup>, K. Suruliz<sup>138</sup>, S. Sushkov<sup>11</sup>, G. Susinno<sup>36a,36b</sup>, M.R. Sutton<sup>148</sup>, Y. Suzuki<sup>65</sup>, Y. Suzuki<sup>66</sup>, M. Svatos<sup>124</sup>, Yu.M. Sviridov<sup>127</sup>, S. Swedish<sup>167</sup>, I. Sykora<sup>143a</sup>, T. Sykora<sup>125</sup>, B. Szeless<sup>29</sup>, J. Sánchez<sup>166</sup>, D. Ta<sup>104</sup>, K. Tackmann<sup>41</sup>, A. Taffard<sup>162</sup>, R. Tafiout<sup>158a</sup>, N. Taiblum<sup>152</sup>, Y. Takahashi<sup>100</sup>, H. Takai<sup>24</sup>, R. Takashima<sup>68</sup>, H. Takeda<sup>66</sup>, T. Takeshita<sup>139</sup>, Y. Takubo<sup>65</sup>, M. Talby<sup>82</sup>, A. Talyshev<sup>106,f</sup>, M.C. Tamsett<sup>24</sup>, J. Tanaka<sup>154</sup>, R. Tanaka<sup>114</sup>, S. Tanaka<sup>130</sup>, S. Tanaka<sup>65</sup>, Y. Tanaka<sup>99</sup>, A.J. Tanasijczuk<sup>141</sup>, K. Tani<sup>66</sup>, N. Tannoury<sup>82</sup>, G.P. Tappern<sup>29</sup>, S. Tapprogge<sup>80</sup>, D. Tardif<sup>157</sup>, S. Tarem<sup>151</sup>, F. Tarrade<sup>28</sup>, G.F. Tartarelli<sup>88a</sup>, P. Tas<sup>125</sup>, M. Tasevsky<sup>124</sup>, E. Tassi<sup>36a,36b</sup>, M. Tatarkhanov<sup>14</sup>, Y. Tayalati<sup>134d</sup>, C. Taylor<sup>76</sup>, F.E. Taylor<sup>91</sup>, G.N. Taylor<sup>85</sup>, W. Taylor<sup>158b</sup>, M. Teinturier<sup>114</sup>, M. Teixeira Dias Castanheira<sup>74</sup>, P. Teixeira-Dias<sup>75</sup>, K.K. Temming<sup>48</sup>, H. Ten Kate<sup>29</sup>, P.K. Teng<sup>150</sup>, S. Terada<sup>65</sup>, K. Terashi<sup>154</sup>, J. Terron<sup>79</sup>, M. Testa<sup>47</sup>, R.J. Teuscher<sup>157,j</sup>, J. Thadome<sup>173</sup>, J. Therhaag<sup>20</sup>, T. Theveneaux-Pelzer<sup>77</sup>, M. Thioye<sup>174</sup>, S. Thoma<sup>48</sup>, J.P. Thomas<sup>17</sup>, E.N. Thompson<sup>34</sup>, P.D. Thompson<sup>17</sup>, P.D. Thompson<sup>157</sup>, A.S. Thompson<sup>53</sup>, L.A. Thomsen<sup>35</sup>, E. Thomson<sup>119</sup>, M. Thomson<sup>27</sup>, R.P. Thun<sup>86</sup>, F. Tian<sup>34</sup>, M.J. Tibbetts<sup>14</sup>, T. Tic<sup>124</sup>, V.O. Tikhomirov<sup>93</sup>, Y.A. Tikhonov<sup>106,f</sup>, S. Timoshenko<sup>95</sup>, P. Tipton<sup>174</sup>, F.J. Tique Aires Viegas<sup>29</sup>, S. Tisserant<sup>82</sup>, B. Toczec<sup>37</sup>, T. Todorov<sup>4</sup>, S. Todorova-Nova<sup>160</sup>, B. Toggerson<sup>162</sup>, J. Tojo<sup>65</sup>, S. Tokár<sup>143a</sup>,



K. Tokunaga<sup>66</sup>, K. Tokushuku<sup>65</sup>, K. Tollefson<sup>87</sup>, M. Tomoto<sup>100</sup>, L. Tompkins<sup>30</sup>, K. Toms<sup>102</sup>, G. Tong<sup>32a</sup>, A. Tonoyan<sup>13</sup>, C. Topfel<sup>16</sup>, N.D. Topilin<sup>64</sup>, I. Torchiani<sup>29</sup>, E. Torrence<sup>113</sup>, H. Torres<sup>77</sup>, E. Torró Pastor<sup>166</sup>, J. Toth<sup>82,aa</sup>, F. Touchard<sup>82</sup>, D.R. Tovey<sup>138</sup>, T. Trefzger<sup>172</sup>, L. Tremblet<sup>29</sup>, A. Tricoli<sup>29</sup>, I.M. Trigger<sup>158a</sup>, S. Trincas-Duvoid<sup>77</sup>, T.N. Trinh<sup>77</sup>, M.F. Tripiana<sup>69</sup>, W. Trischuk<sup>157</sup>, A. Trivedi<sup>24,z</sup>, B. Trocmé<sup>55</sup>, C. Troncon<sup>88a</sup>, M. Trottier-McDonald<sup>141</sup>, M. Trzebinski<sup>38</sup>, A. Trzupek<sup>38</sup>, C. Tsarouchas<sup>29</sup>, J.C.-L. Tseng<sup>117</sup>, M. Tsiakiris<sup>104</sup>, P.V. Tsiarehka<sup>89</sup>, D. Tsionou<sup>4,ae</sup>, G. Tsipolitis<sup>9</sup>, V. Tsiskaridze<sup>48</sup>, E.G. Tskhadadze<sup>51a</sup>, I.I. Tsukerman<sup>94</sup>, V. Tsulaia<sup>14</sup>, J.-W. Tsung<sup>20</sup>, S. Tsuno<sup>65</sup>, D. Tsybychev<sup>147</sup>, A. Tua<sup>138</sup>, A. Tudorache<sup>25a</sup>, V. Tudorache<sup>25a</sup>, J.M. Tuggle<sup>30</sup>, M. Turala<sup>38</sup>, D. Turecek<sup>126</sup>, I. Turk Cakir<sup>3e</sup>, E. Turlay<sup>104</sup>, R. Turra<sup>88a,88b</sup>, P.M. Tuts<sup>34</sup>, A. Tykhonov<sup>73</sup>, M. Tylmad<sup>145a,145b</sup>, M. Tyndel<sup>128</sup>, G. Tzanakos<sup>8</sup>, K. Uchida<sup>20</sup>, I. Ueda<sup>154</sup>, R. Ueno<sup>28</sup>, M. Uglund<sup>13</sup>, M. Uhlenbrock<sup>20</sup>, M. Uhrmacher<sup>54</sup>, F. Ukegawa<sup>159</sup>, G. Unal<sup>29</sup>, D.G. Underwood<sup>5</sup>, A. Undrus<sup>24</sup>, G. Unel<sup>162</sup>, Y. Unno<sup>65</sup>, D. Urbaniec<sup>34</sup>, G. Usai<sup>7</sup>, M. Uslenghi<sup>118a,118b</sup>, L. Vacavant<sup>82</sup>, V. Vacek<sup>126</sup>, B. Vachon<sup>84</sup>, S. Vahsen<sup>14</sup>, J. Valenta<sup>124</sup>, P. Valente<sup>131a</sup>, S. Valentinetti<sup>19a,19b</sup>, S. Valkar<sup>125</sup>, E. Valladolid Gallego<sup>166</sup>, S. Vallecorsa<sup>151</sup>, J.A. Valls Ferrer<sup>166</sup>, H. van der Graaf<sup>104</sup>, E. van der Kraaij<sup>104</sup>, R. Van Der Leeuw<sup>104</sup>, E. van der Poel<sup>104</sup>, D. van der Ster<sup>29</sup>, N. van Eldik<sup>83</sup>, P. van Gemmeren<sup>5</sup>, Z. van Kesteren<sup>104</sup>, I. van Vulpen<sup>104</sup>, M. Vanadia<sup>98</sup>, W. Vandelli<sup>29</sup>, G. Vandoni<sup>29</sup>, A. Vaniachine<sup>5</sup>, P. Vankov<sup>41</sup>, F. Vannucci<sup>77</sup>, F. Varela Rodriguez<sup>29</sup>, R. Vari<sup>131a</sup>, E.W. Varnes<sup>6</sup>, T. Varol<sup>93</sup>, D. Varouchas<sup>14</sup>, A. Vartapetian<sup>7</sup>, K.E. Varvell<sup>149</sup>, V.I. Vassilakopoulos<sup>56</sup>, F. Vazeille<sup>33</sup>, T. Vazquez Schroeder<sup>54</sup>, G. 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